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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

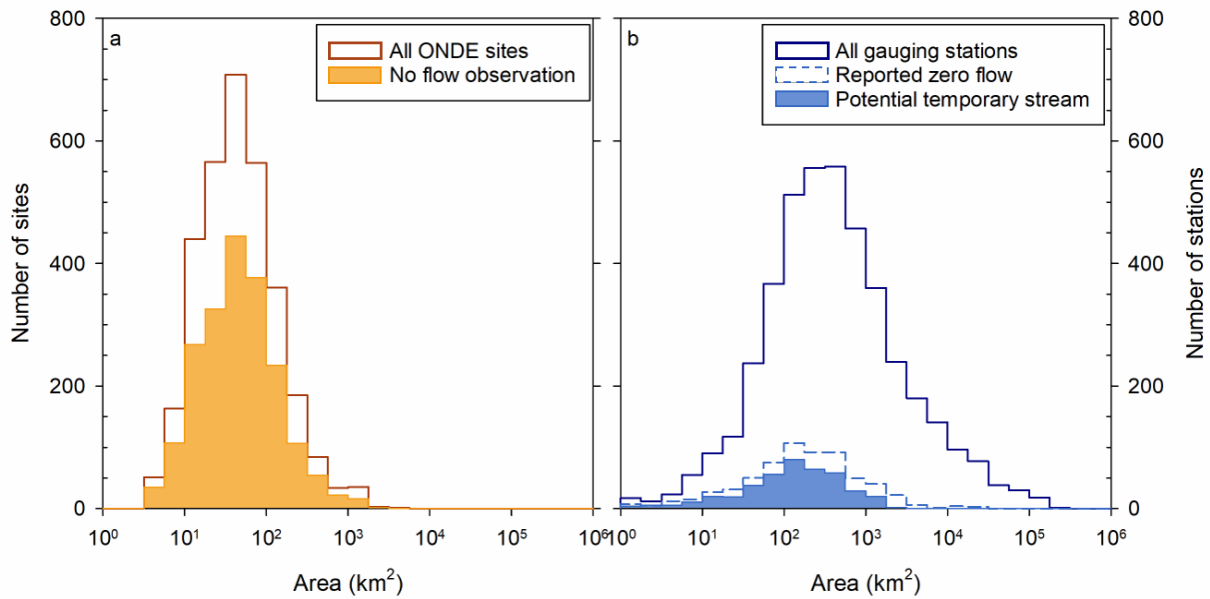
35 extreme rainfall events (Buttle *et al.*, 2012). The terms used for these non-perennial streams vary
36 (Busch *et al.*, 2020) and more classes can be defined to describe the occurrence of pools with
37 standing water (Gallart *et al.*, 2017). Here we use the term temporary stream to refer to all 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*
66 *al.*, 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

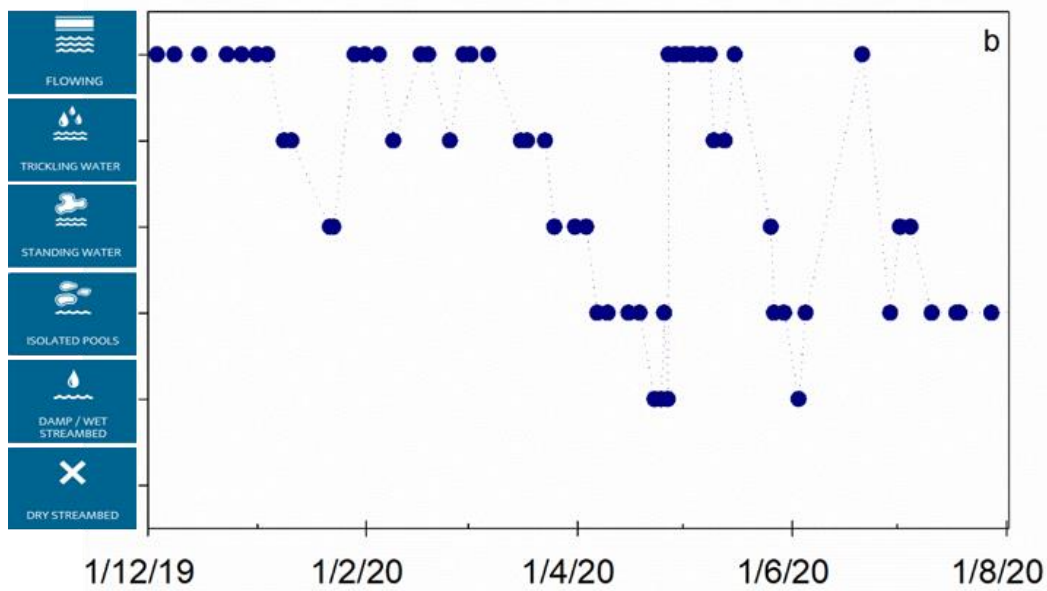
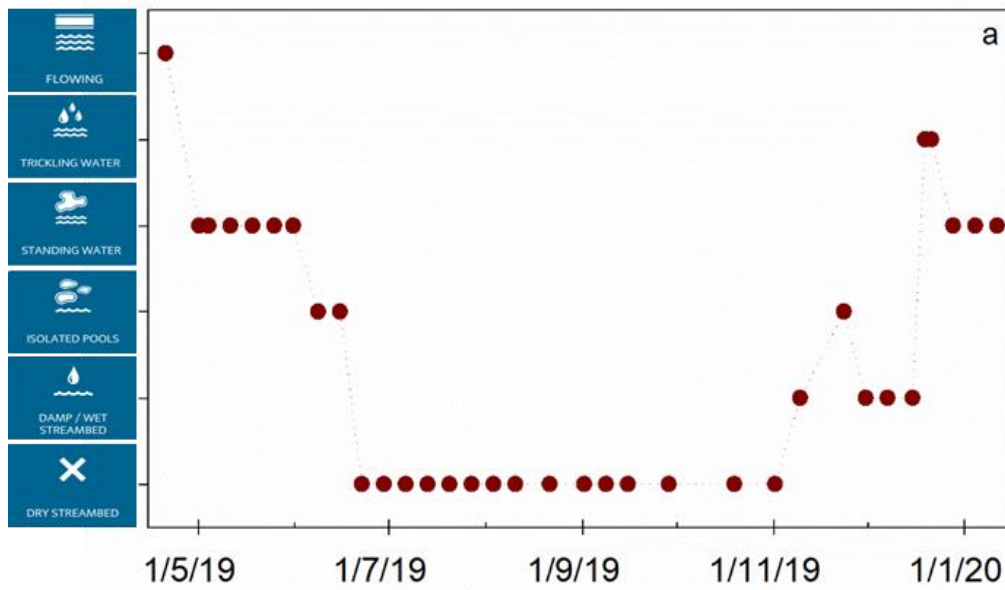
125 dry (Gallart *et al.*, 2012; Bonada *et al.*, 2020). Gauging stations are designed to measure flow, not to
126 provide information on the presence of pools. Pools of standing water are common and provide
127 important refugia during dry periods (e.g., Marshall *et al.*, 2016). At 39% of the sites 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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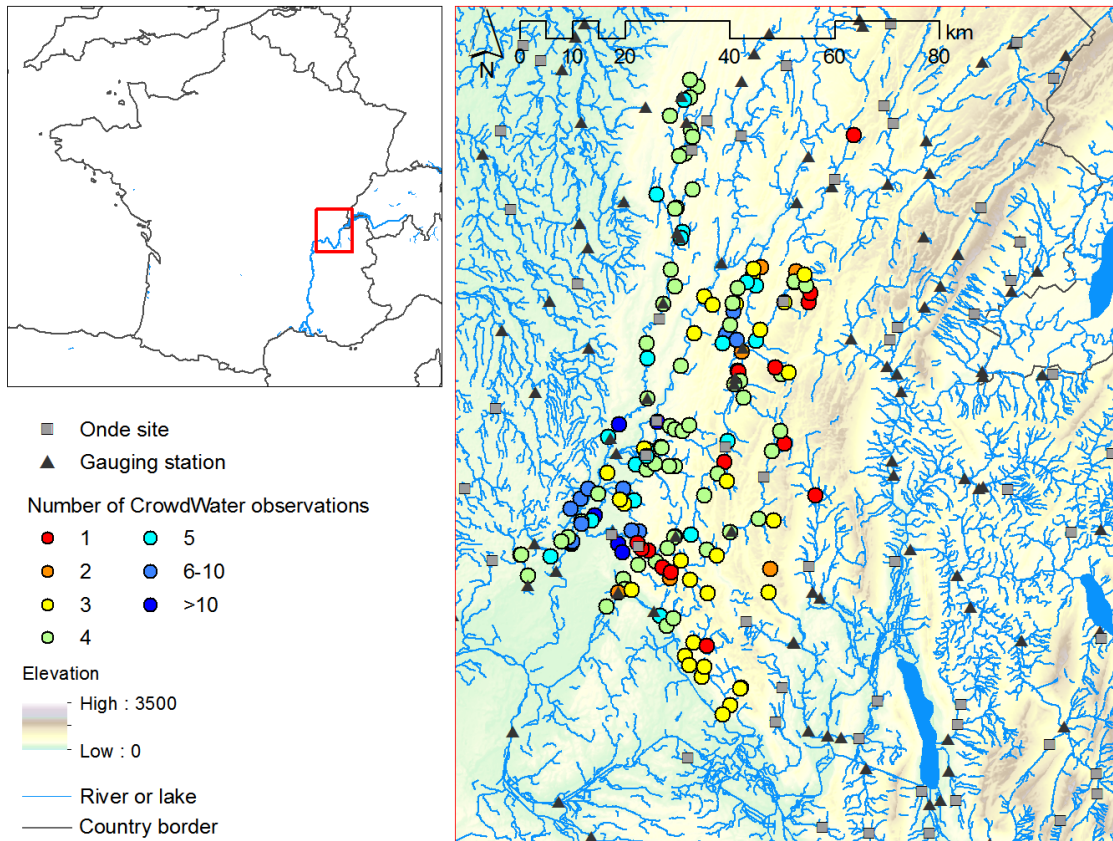
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Figure 2. Examples of eight-month time series of observations of the hydrological state of temporary streams made with the CrowdWater app for a site in Portugal (a) and a site in Switzerland (b). Note that the two Figures show a different period. Source: <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

232 **References**

- 233 Acuña V, Muñoz I, Giorgi A, Omella M, Sabater F, Sabater S. 2005. Drought and postdrought recovery
234 cycles in an intermittent Mediterranean stream: structural and functional aspects. *Journal of*
235 *the North American Benthological Society*, **24**: 919-933. DOI: 10.1899/04-078.1.
- 236 Ågren A, Lidberg W, Ring E. 2015. Mapping Temporal Dynamics in a Forest Stream Network—
237 Implications for Riparian Forest Management. *Forests*, **6**: 2982.
- 238 Allen DC, Kopp DA, Costigan KH, Datry T, Hugueny B, Turner DS, Bodner GS, Flood TJ. 2019. Citizen
239 scientists document long-term streamflow declines in intermittent rivers of the desert
240 southwest, USA. *Freshwater Science*, **38**: 244-256. DOI: 10.1086/701483.
- 241 Armstrong A, Stedman RC, Bishop JA, Sullivan PJ. 2012. What’s a Stream Without Water?
242 Disproportionality in Headwater Regions Impacting Water Quality. *Environmental*
243 *Management*, **50**: 849-860. DOI: 10.1007/s00267-012-9928-0.
- 244 Assendelft RS, van Meerveld HJ. 2019. A Low-Cost, Multi-Sensor System to Monitor Temporary
245 Stream Dynamics in Mountainous Headwater Catchments. *Sensors*, **19**: 4645.
- 246 Beaufort A, Carreau J, Sauquet E. 2019. A classification approach to reconstruct local daily drying
247 dynamics at headwater streams. *Hydrological Processes*, **33**: 1896-1912. DOI:
248 10.1002/hyp.13445.
- 249 Benstead JP, Leigh DS. 2012. An expanded role for river networks. *Nature Geosci*, **5**: 678-679.
- 250 Bhamjee R, Lindsay JB. 2011. Ephemeral stream sensor design using state loggers. *Hydrol. Earth Syst.*
251 *Sci. J1 - HESS*, **15**: 1009-1021.
- 252 Bhamjee R, Lindsay JB, Cockburn J. 2016. Monitoring ephemeral headwater streams: a paired-sensor
253 approach. *Hydrological Processes*, **30**: 888-898. DOI: 10.1002/hyp.10677.
- 254 Bishop K, Buffam I, Erlandsson M, Fölster J, Laudon H, Seibert J, Temnerud J. 2008. Aqua Incognita:
255 the unknown headwaters. *Hydrological Processes*, **22**: 1239-1242.
- 256 Blasch KW, Ferré TPA, Christensen AH, Hoffmann JP. 2002. New Field Method to Determine
257 Streamflow Timing Using Electrical Resistance Sensors. *Vadose Zone Journal*, **1**: 289-299. DOI:
258 10.2113/1.2.289.
- 259 Blöschl G, Bierkens MFP, Chambel A, Cudennec C, Destouni G, Fiori A, Kirchner JW, McDonnell JJ,
260 Savenije HHG, Sivapalan M, Stumpp C, Toth E, Volpi E, Carr G, Lupton C, Salinas J, Széles B,
261 Viglione A, Aksoy H, Allen ST, Amin A, Andréassian V, Arheimer B, Aryal SK, Baker V, Bardsley
262 E, Barendrecht MH, Bartosova A, Batelaan O, Berghuijs WR, Beven K, Blume T, Bogaard T,
263 Borges de Amorim P, Böttcher ME, Boulet G, Breinl K, Brilly M, Brocca L, Buytaert W,
264 Castellarin A, Castelletti A, Chen X, Chen Y, Chen Y, Chiffard P, Claps P, Clark MP, Collins AL,
265 Croke B, Dathe A, David PC, de Barros FPJ, de Rooij G, Di Baldassarre G, Driscoll JM,
266 Duethmann D, Dwivedi R, Eris E, Farmer WH, Feiccabrino J, Ferguson G, Ferrari E, Ferraris S,
267 Fersch B, Finger D, Foglia L, Fowler K, Gartsman B, Gascoin S, Gaume E, Gelfan A, Geris J,
268 Gharari S, Gleeson T, Glendell M, Gonzalez Bevacqua A, González-Dugo MP, Grimaldi S,
269 Gupta AB, Guse B, Han D, Hannah D, Harpold A, Haun S, Heal K, Helfricht K, Herrnegger M,
270 Hipsev M, Hlaváčková H, Hohmann C, Holko L, Hopkinson C, Hrachowitz M, Illangasekare TH,
271 Inam A, Innocente C, Istanbuluoglu E, Jarihani B, Kalantari Z, Kalvans A, Khanal S, Khatami S,
272 Kiesel J, Kirkby M, Knoben W, Kochanek K, Kohnová S, Kolechkin A, Krause S, Kremer D,
273 Kreibich H, Kunstmann H, Lange H, Liberato MLR, Lindquist E, Link T, Liu J, Loucks DP, Luce C,
274 Mahé G, Makarieva O, Malard J, Mashtayeva S, Maskey S, Mas-Pla J, Mavrova-Guirguinova
275 M, Mazzoleni M, Mernild S, Misstear BD, Montanari A, Müller-Thomy H, Nabizadeh A, Nardi
276 F, Neale C, Nesterova N, Nurtaev B, Odongo VO, Panda S, Pande S, Pang Z,
277 Papacharalampous G, Perrin C, Pfister L, Pimentel R, Polo MJ, Post D, Prieto Sierra C, Ramos
278 M-H, Renner M, Reynolds JE, Ridolfi E, Rigon R, Riva M, Robertson DE, Rosso R, Roy T, Sá
279 JHM, Salvadori G, Sandells M, Schaefli B, Schumann A, Scolobig A, Seibert J, Servat E, Shafiei
280 M, Sharma A, Sidibe M, Sidle RC, Skaugen T, Smith H, Spiessl SM, Stein L, Steinsland I,
281 Strasser U, Su B, Szolgay J, Tarboton D, Tauro F, Thirel G, Tian F, Tong R, Tussupova K, Tyrallis
282 H, Uijlenhoet R, van Beek R, van der Ent RJ, van der Ploeg M, Van Loon AF, van Meerveld I,

283 van Nooijen R, van Oel PR, Vidal J-P, von Freyberg J, Vorogushyn S, Wachniew P, Wade AJ,
284 Ward P, Westerberg IK, White C, Wood EF, Woods R, Xu Z, Yilmaz KK, Zhang Y. 2019. Twenty-
285 three unsolved problems in hydrology (UPH) – a community perspective. *Hydrological*
286 *Sciences Journal*, **64**: 1141-1158. DOI: 10.1080/02626667.2019.1620507.

287 Bonada N, Cañedo-Argüelles M, Gallart F, von Schiller D, Fortuño P, Latron J, Llorens P, Múrria C,
288 Soria M, Vinyoles D, Cid N. 2020. Conservation and Management of Isolated Pools in
289 Temporary Rivers. *Water*, **12**: 2870.

290 Borg Galea A, Sadler JP, Hannah DM, Datry T, Dugdale SJ. 2019. Mediterranean intermittent rivers
291 and ephemeral streams: Challenges in monitoring complexity. *Ecohydrology*, **12**: e2149. DOI:
292 10.1002/eco.2149.

293 Brock MA, Nielsen DL, Shiel RJ, Green JD, Langley JD. 2003. Drought and aquatic community
294 resilience: the role of eggs and seeds in sediments of temporary wetlands. *Freshwater*
295 *Biology*, **48**: 1207-1218. DOI: 10.1046/j.1365-2427.2003.01083.x.

296 Busch MH, Costigan KH, Fritz KM, Datry T, Krabbenhoft CA, Hammond JC, Zimmer M, Olden JD,
297 Burrows RM, Dodds WK, Boersma KS, Shanafield M, Kampf SK, Mims MC, Bogan MT, Ward
298 AS, Perez Rocha M, Godsey S, Allen GH, Blaszcak JR, Jones CN, Allen DC. 2020. What's in a
299 Name? Patterns, Trends, and Suggestions for Defining Non-Perennial Rivers and Streams.
300 *Water Air and Soil Pollution*, **12**: 1980. DOI: <https://doi.org/10.3390/w12071980>.

301 Buttle JM, Boon S, Peters DL, Spence C, van Meerveld HJ, Whitfield PH. 2012. An Overview of
302 Temporary Stream Hydrology in Canada. *Canadian Water Resources Journal*, **37**: 279-310.

303 Calsamiglia A, Gago J, Garcia-Comendador J, Bernat JF, Calvo-Cases A, Estrany J. 2020. Evaluating
304 functional connectivity in a small agricultural catchment under contrasting flood events by
305 using UAV. *Earth Surface Processes and Landforms*, **45**: 800-815. DOI: 10.1002/esp.4769.

306 Caruso BS. 2011. Science and policy integration issues for stream and wetland jurisdictional
307 determinations in a semi-arid region of the western U.S. *Wetlands Ecology and Management*,
308 **19**: 351-371. DOI: 10.1007/s11273-011-9221-7.

309 Caruso BS, Haynes J. 2011. Biophysical-Regulatory Classification and Profiling of Streams Across
310 Management Units and Ecoregions1. *JAWRA Journal of the American Water Resources*
311 *Association*, **47**: 386-407. DOI: 10.1111/j.1752-1688.2010.00522.x.

312 Chapin TP, Todd AS, Zeigler MP. 2014. Robust, low-cost data loggers for stream temperature, flow
313 intermittency, and relative conductivity monitoring. *Water Resources Research*, **50**: 6542-
314 6548. DOI: 10.1002/2013wr015158.

315 Cipriani T, Tilmant F, Branger F, Sauquet E, Datry T. 2014. Impact of climate change on aquatic
316 ecosystems along the Asse river network. In: *Proceedings of FRIEND-Water 2014*, pp: 6 p.

317 Constantz J. 2008. Heat as a tracer to determine streambed water exchanges. *Water Resources*
318 *Research*, **44**.

319 Datry T, Arscott D, Sabater S. 2011. Recent perspectives on temporary river ecology. *Aquatic Sciences*
320 *- Research Across Boundaries*, **73**: 453-457.

321 De Girolamo AM, Bouraoui F, Buffagni A, Pappagallo G, Lo Porto A. 2017. Hydrology under climate
322 change in a temporary river system: Potential impact on water balance and flow regime.
323 *River Research and Applications*, **33**: 1219-1232. DOI: 10.1002/rra.3165.

324 Doering M, Uehlinger U, Rotach A, Schlaepfer DR, Tockner K. 2007. Ecosystem expansion and
325 contraction dynamics along a large Alpine alluvial corridor (Tagliamento River, Northeast
326 Italy). *Earth Surface Processes and Landforms*, **32**: 1693-1704.

327 Döll P, Schmied HM. 2012. How is the impact of climate change on river flow regimes related to the
328 impact on mean annual runoff? A global-scale analysis. *Environmental Research Letters*, **7**:
329 014037. DOI: 10.1088/1748-9326/7/1/014037.

330 Durighetto N, Vingiani F, Bertassello LE, Camporese M, Botter G. 2020. Intraseasonal Drainage
331 Network Dynamics in a Headwater Catchment of the Italian Alps. *Water Resources Research*,
332 **56**: e2019WR025563. DOI: 10.1029/2019wr025563.

333 Fortesa J, Ricci GF, García-Comendador J, Gentile F, Estrany J, Sauquet E, Datry T, De Girolamo AM.
334 2021. Analysing hydrological and sediment transport regime in two Mediterranean

335 intermittent rivers. *CATENA*, **196**: 104865. DOI:
336 <https://doi.org/10.1016/j.catena.2020.104865>.

337 Fritz KM, Hagenbuch E, D'Amico E, Reif M, Wington PJ, Leibowitz SG, Comeleo RL, Ebersole JL,
338 Nadeau T-L. 2013. Comparing the Extent and Permanence of Headwater Streams From Two
339 Field Surveys to Values From Hydrographic Databases and Maps. *JAWRA Journal of the*
340 *American Water Resources Association*, **49**: 867-882. DOI: 10.1111/jawr.12040.

341 Fritz KM, Nadeau T-L, Kelso JE, Beck WS, Mazor RD, Harrington RA, Topping BJ. 2020. Classifying
342 Streamflow Duration: The Scientific Basis and an Operational Framework for Method
343 Development. *Water*, **12**: 2545.

344 Gallart F, Cid N, Latron J, Llorens P, Bonada N, Jeuffroy J, Jiménez-Argudo S-M, Vega R-M, Solà C,
345 Soria M, Bardina M, Hernández-Casahuga A-J, Fidalgo A, Estrela T, Munné A, Prat N. 2017.
346 TREHS: An open-access software tool for investigating and evaluating temporary river
347 regimes as a first step for their ecological status assessment. *Science of The Total*
348 *Environment*, **607-608**: 519-540. DOI: <https://doi.org/10.1016/j.scitotenv.2017.06.209>.

349 Gallart F, Prat N, García-Roger EM, Latron J, Rieradevall M, Llorens P, Barberá GG, Brito D, De
350 Girolamo AM, Lo Porto A, Buffagni A, Erba S, Neves R, Nikolaidis NP, Perrin JL, Querner EP,
351 Quiñonero JM, Tournoud MG, Tzoraki O, Skoulidakis N, Gómez R, Sánchez-Montoya MM,
352 Froebrich J. 2012. A novel approach to analysing the regimes of temporary streams in
353 relation to their controls on the composition and structure of aquatic biota. *Hydrol. Earth*
354 *Syst. Sci.*, **16**: 3165-3182. DOI: DOI:10.5194/hess-16-3165-2012.

355 Godsey SE, Kirchner JW. 2014. Dynamic, discontinuous stream networks: hydrologically driven
356 variations in active drainage density, flowing channels and stream order. *Hydrological*
357 *Processes*, **28**: 5791-5803. DOI: 10.1002/hyp.10310.

358 González-Ferreras AM, Barquín J. 2017. Mapping the temporary and perennial character of whole
359 river networks. *Water Resources Research*, **53**: 6709-6724. DOI: 10.1002/2017wr020390.

360 Goulsbra CS, Lindsay JB, Evans MG. 2009. A new approach to the application of electrical resistance
361 sensors to measuring the onset of ephemeral streamflow in wetland environments. *Water*
362 *Resour. Res.*, **45**: W09501, doi:09510.01029/02009WR007789.

363 Gutiérrez-Jurado KY, Partington D, Batelaan O, Cook P, Shanafield M. 2019. What Triggers
364 Streamflow for Intermittent Rivers and Ephemeral Streams in Low-Gradient Catchments in
365 Mediterranean Climates. *Water Resources Research*, **55**: 9926-9946. DOI:
366 10.1029/2019wr025041.

367 Hale RL, Godsey SE. 2019. Dynamic stream network intermittence explains emergent dissolved
368 organic carbon chemostasis in headwaters. *Hydrological Processes*, **33**: 1926-1936. DOI:
369 10.1002/hyp.13455.

370 Hansen WF. 2001. Identifying stream types and management implications. *Forest Ecology and*
371 *Management*, **143**: 39-46. DOI: [http://dx.doi.org/10.1016/S0378-1127\(00\)00503-X](http://dx.doi.org/10.1016/S0378-1127(00)00503-X).

372 Harrigan S, Hannaford J, Muchan K, Marsh TJ. 2018. Designation and trend analysis of the updated
373 UK Benchmark Network of river flow stations: the UKBN2 dataset. *Hydrol. Res.*, **49**: 552-567.
374 DOI: 10.2166/nh.2017.058.

375 Hladyz S, Watkins SC, Whitworth KL, Baldwin DS. 2011. Flows and hypoxic blackwater events in
376 managed ephemeral river channels. *Journal of Hydrology*, **401**: 117-125.

377 Jaeger KL, Olden JD, Pelland NA. 2014. Climate change poised to threaten hydrologic connectivity and
378 endemic fishes in dryland streams. *Proc Natl Acad Sci U S A*, **111**: 13894-13899. DOI:
379 10.1073/pnas.1320890111.

380 Jaeger KL, Sando R, McShane RR, Dunham JB, Hockman-Wert DP, Kaiser KE, Hafen K, Risley JC, Blasch
381 KW. 2019. Probability of Streamflow Permanence Model (PROSPER): A spatially continuous
382 model of annual streamflow permanence throughout the Pacific Northwest. *Journal of*
383 *Hydrology X*, **2**: 100005. DOI: <https://doi.org/10.1016/j.hydroa.2018.100005>.

384 Jensen CK, McGuire KJ, Prince PS. 2017. Headwater stream length dynamics across four
385 physiographic provinces of the Appalachian Highlands. *Hydrological Processes*, **31**: 3350-
386 3363. DOI: 10.1002/hyp.11259.

387 Kampf SK, Strobl B, Hammond J, Anenberg A, Etter S, Martin C, Puntenney-Desmond K, Seibert J, van
388 Meerveld I. 2018. Testing the waters: Mobile apps for crowdsourced streamflow data. *Eos*,
389 **99**. DOI: <https://doi.org/10.1029/2018EO096355>. .

390 Konrad C, Rumsey C. 2019. Estimating minimum streamflow from measurements at ungauged sites in
391 regions with streamflow-gauging networks. *Hydrological Processes*, **33**: 2057-2067. DOI:
392 10.1002/hyp.13452.

393 Larned ST, Datry T, Arscott DB, Tockner K. 2010. Emerging concepts in temporary-river ecology.
394 *Freshwater Biology*, **55**: 717-738.

395 Levick L, Fonseca J, Goodrich DC, Hernandez M, Semmens D, Stromberg J, Leidy R, Scianni M, Guertin
396 DP, Tluczek M, W. K. 2008. The Ecological and Hydrological Significance of Ephemeral and
397 Intermittent Streams in the Arid and Semi-arid American Southwest In: U.S. Environmental
398 Protection Agency and USDA/ARS Southwest Watershed Research Center, EPA/600/R-
399 08/134, ARS/233046. Published 11/2008.

400 Magand C, Alves MH, Calleja E, Datry T, Dörflinger G, England J, ..., Von Schiller D. 2020. Intermittent
401 rivers and ephemeral streams: what water managers need to know. Zenodo,
402 <http://doi.org/10.5281/zenodo.3888474>.

403 Malard F, Uehlinger U, Zah R, Tockner K. 2006. Flood-pulse and riverscape dynamics in a braided
404 glacial river. *Ecology*, **87**: 704-716.

405 Marshall JC, Menke N, Crook DA, Lobegeiger JS, Balcombe SR, Huey JA, Fawcett JH, Bond NR, Starkey
406 AH, Sternberg D, Linke S, Arthington AH. 2016. Go with the flow: the movement behaviour of
407 fish from isolated waterhole refugia during connecting flow events in an intermittent dryland
408 river. *Freshwater Biology*, **61**: 1242-1258. DOI: 10.1111/fwb.12707.

409 Meyer JL, Strayer DL, Wallace JB, Eggert SL, Helfman GS, Leonard NE. 2007. The contribution of
410 headwater streams to biodiversity in river networks. *Journal of the American Water
411 Resources Association*, **43**: 86-103.

412 Nikolaidis NP, Demetropoulou L, Froebrich J, Jacobs C, Gallart F, Prat N, Porto AL, Campana C,
413 Papadoulakis V, Skoulikidis N, Davy T, Bidoglio G, Bouraoui F, Kirkby M, Tournoud M-G,
414 Polesello S, Barberá GG, Cooper D, Gomez R, Sánchez-Montoya MdM, Latron J, De Girolamo
415 AM, Perrin J-L. 2013. Towards sustainable management of Mediterranean river basins: policy
416 recommendations on management aspects of temporary streams. *Water Policy*, **15**: 830-849.
417 DOI: 10.2166/wp.2013.158.

418 Paillex A, Siebers AR, Ebi C, Mesman J, Robinson CT. 2020. High stream intermittency in an alpine
419 fluvial network: Val Roseg, Switzerland. *Limnology and Oceanography*, **65**: 557-568. DOI:
420 10.1002/lno.11324.

421 Pařil P, Leigh C, Polářek M, Sarremejane R, ezňíková P, Dostálová A, Stubbington R. 2019. Short-term
422 streambed drying events alter amphipod population structure in a central European stream.
423 *Fundamental and Applied Limnology / Archiv für Hydrobiologie*, **193**: 51-64.

424 Pate AA, Segura C, Bladon KD. 2020. Streamflow permanence in headwater streams across four
425 geomorphic provinces in Northern California. *Hydrological Processes*, **34**. DOI:
426 <https://doi.org/10.1002/hyp.13889>.

427 Peters DL, Boon S, Huxter E, Spence C, van Meerveld HJ, Whitfield PH. 2012. ZeroFlow: A PUB
428 (Prediction in Ungauged Basins) Workshop on Temporary Streams - Summary of Workshop
429 Discussions and Future Directions. *Canadian Water Resources Journal*, **37**: 425-431.

430 Pocock MJO, Chapman D, Sheppard L, Roy HE. 2013. Developing a Strategic Framework to Support
431 Citizen Science Implementation in SEPA. In: Final Report on behalf of SEPA, NERC Centre for
432 Ecology & Hydrology, pp: 65.

433 Prancevic JP, Kirchner JW. 2019. Topographic Controls on the Extension and Retraction of Flowing
434 Streams. *Geophysical Research Letters*, **46**: 2084-2092. DOI: 10.1029/2018gl081799.

435 Pumo D, Caracciolo D, Viola F, Noto LV. 2016. Climate change effects on the hydrological regime of
436 small non-perennial river basins. *Science of The Total Environment*, **542**: 76-92. DOI:
437 <https://doi.org/10.1016/j.scitotenv.2015.10.109>.

438 Querner EP, Froebrich J, Gallart F, Cazemier MM, Tzoraki O. 2016. Simulating streamflow variability
439 and aquatic states in temporary streams using a coupled groundwater-surface water model.
440 Hydrological Sciences Journal, **61**: 146-161. DOI: 10.1080/02626667.2014.983514.

441 Reynolds LV, Shafroth PB, LeRoy Poff N. 2015. Modeled intermittency risk for small streams in the
442 Upper Colorado River Basin under climate change. Journal of Hydrology, **523**: 768-780. DOI:
443 <http://dx.doi.org/10.1016/j.jhydrol.2015.02.025>.

444 Romaní A, Vázquez E, Butturini A. 2006. Microbial Availability and Size Fractionation of Dissolved
445 Organic Carbon After Drought in an Intermittent Stream: Biogeochemical Link Across the
446 Stream–Riparian Interface. Microb Ecol, **52**: 501-512. DOI: 10.1007/s00248-006-9112-2.

447 Ronan AD, Prudic DE, Thodal CE, Constantz J. 1998. Field study and simulation of diurnal temperature
448 effects on infiltration and variably saturated flow beneath an ephemeral stream. Water
449 Resources Research, **34**: 2137-2153. DOI: 10.1029/98wr01572.

450 Russell PP, Gale SM, Muñoz B, Dorney JR, Rubino MJ. 2015. A Spatially Explicit Model for Mapping
451 Headwater Streams. JAWRA Journal of the American Water Resources Association, **51**: 226-
452 239. DOI: 10.1111/jawr.12250.

453 Sarremejane R, England J, Sefton CEM, Parry S, Eastman M, Stubbington R. in press. Local and
454 regional drivers influence how aquatic community diversity, resistance and resilience vary in
455 response to drying. Oikos, **n/a**. DOI: 10.1111/oik.07645.

456 Sauquet E, van Meerveld I, Gallart F, Sefton C, Parry S, Gauster T, ..., Želazny M. 2020. A catalogue of
457 European intermittent rivers and ephemeral streams.

458 Sefton CEM, Parry S, England J, Angell G. 2019. Visualising and quantifying the variability of
459 hydrological state in intermittent rivers. Fundamental and Applied Limnology / Archiv f??r
460 Hydrobiologie, **193**: 21-38.

461 Seibert J, van Meerveld HJ, Etter S, Strobl B, Assendelft R, Hummer P. 2019. Wasserdaten sammeln
462 mit dem Smartphone – Wie können Menschen messen, was hydrologische Modelle
463 brauchen? Hydrologie & Wasserbewirtschaftung, **63**.

464 Shanafield M, Godsey S, Datry T, Hale R, Zipper SC, Costigan K, Krabbenhoft CA, Dodds WK, Zimmer
465 M, Allen DC, Bogan M, Kaiser KE, Burrows RM, Hammond JC, Busch M, Kampf S, Mims MC,
466 Burgin A, Olden JD. 2020. Science gets up to speed on dry rivers,. Eos, **101**,
467 <https://doi.org/10.1029/2020EO139902>.

468 Sherrod L, Sauck W, Werkema DD. 2012. A Low-Cost, In Situ Resistivity and Temperature Monitoring
469 System. Ground Water Monitoring & Remediation, **32**: 31-39.

470 Snelder TH, Datry T, Lamouroux N, Larned ST, Sauquet E, Pella H, Catalogne C. 2013. Regionalization
471 of patterns of flow intermittence from gauging station records. Hydrol. Earth Syst. Sci., **17**:
472 2685-2699. DOI: 10.5194/hess-17-2685-2013.

473 Spence C, Mengistu S. 2016. Deployment of an unmanned aerial system to assist in mapping an
474 intermittent stream. Hydrological Processes, **30**: 493-500. DOI: 10.1002/hyp.10597.

475 Stanley EH, Fisher SG, Grimm NB. 1997. Ecosystem expansion and contraction in streams. Bioscience:
476 427-435.

477 Steward AL, von Schiller D, Tockner K, Marshall JC, Bunn SE. 2012. When the river runs dry: human
478 and ecological values of dry riverbeds. Frontiers in Ecology and the Environment, **10**: 202-
479 209.

480 Stoll S, Weiler M. 2010. Explicit simulations of stream networks to guide hydrological modelling in
481 ungauged basins. Hydrol. Earth Syst. Sci. J1 - HESS, **14**: 1435-1448.

482 Stubbington R, England J, Wood PJ, Sefton CEM. 2017. Temporary streams in temperate zones:
483 recognizing, monitoring and restoring transitional aquatic-terrestrial ecosystems. WIREs
484 Water, **4**: e1223. DOI: 10.1002/wat2.1223.

485 Trambly Y, Rutkowska A, Sauquet E, Sefton C, Laaha G, Osuch M, Albuquerque T, Alves M-H, Banasik
486 K, Beaufort A, Brocca L, Camici S, Zoltan C, Dakhlaoui H, De Girolamo A-M, Dörflinger G,
487 Gallart F, Gauster T, Hanich I, Kohnová S, Mediero L, Plamen N, Parry S, Quintana-Segui P,
488 Tzoraki O, Datry T. in press. Trends in flow intermittence for European Rivers. Hydrological
489 Sciences Journal.

490 Turner D, Richter H. 2011. Wet/Dry Mapping: Using Citizen Scientists to Monitor the Extent of
491 Perennial Surface Flow in Dryland Regions. *Environmental Management*, **47**: 497-505. DOI:
492 10.1007/s00267-010-9607-y.

493 Tzoraki O, De Girolamo A-M, Gamvroudis C, Skoulikidis N. 2016. Assessing the flow alteration of
494 temporary streams under current conditions and changing climate by Soil and Water
495 Assessment Tool model. *International Journal of River Basin Management*, **14**: 9-18. DOI:
496 10.1080/15715124.2015.1049182.

497 van Meerveld HJ, Kirchner JW, Vis MJP, Assendelft RS, Seibert J. 2019. Expansion and contraction of
498 the flowing stream network alter hillslope flowpath lengths and the shape of the travel time
499 distribution. *Hydrol. Earth Syst. Sci.*, **23**: 4825-4834. DOI: 10.5194/hess-23-4825-2019.

500 von Schiller D, Bernal S, Dahm CN, Martí E. 2017. Chapter 3.2 - Nutrient and Organic Matter
501 Dynamics in Intermittent Rivers and Ephemeral Streams. In: *Intermittent Rivers and
502 Ephemeral Streams*, Datry T, Bonada N, Boulton A (eds.) Academic Press, pp: 135-160.

503 Ward AS, Schmadel NM, Wondzell SM. 2018. Simulation of dynamic expansion, contraction, and
504 connectivity in a mountain stream network. *Advances in Water Resources*, **114**: 64-82. DOI:
505 <https://doi.org/10.1016/j.advwatres.2018.01.018>.

506 Wington PJ, Moser TJ, Lindeman DR. 2005. Stream network expansion: a riparian water quality
507 factor. *Hydrological Processes*, **19**: 1715-1721.

508 Williamson TN, Agouridis CT, Barton CD, Villines JA, Lant JG. 2015. Classification of Ephemeral,
509 Intermittent, and Perennial Stream Reaches Using a TOPMODEL-Based Approach. *JAWRA
510 Journal of the American Water Resources Association*, **51**: 1739– 1759. DOI: 10.1111/1752-
511 1688.12352.

512 Wohl E. 2017. The significance of small streams. *Frontiers of Earth Science*: 1-10. DOI:
513 10.1007/s11707-017-0647-y.

514 Yu S, Bond NR, Bunn SE, Xu Z, Kennard MJ. 2018. Quantifying spatial and temporal patterns of flow
515 intermittency using spatially contiguous runoff data. *Journal of Hydrology*, **559**: 861-872.
516 DOI: <https://doi.org/10.1016/j.jhydrol.2018.03.009>.

517 Zimmer MA, Kaiser KE, Blaszcak JR, Zipper SC, Hammond JC, Fritz KM, Costigan KH, Hosen J, Godsey
518 SE, Allen GH, Kampf S, Burrows RM, Krabbenhoft CA, Dodds W, Hale R, Olden JD, Shanafield
519 M, DeVecchia AG, Ward AS, Mims MC, Datry T, Bogan MT, Boersma KS, Busch MH, Jones CN,
520 Burgin AJ, Allen DC. 2020. Zero or not? Causes and consequences of zero-flow stream gage
521 readings. *WIREs Water*, **7**: e1436. DOI: 10.1002/wat2.1436.

522