Losing flow in free-flowing Mediterranean-climate streams

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Stream drying is happening globally, with important ecological and social consequences. Most examples of stream drying come from systems influenced by dam operations or those with highly exploited aquifers. Stream drying is also thought to be driven by anthropogenic climate change; however, examples are surprisingly limited. We explored flow trends from the five recognized Mediterranean-climate regions of the world with a focus on unregulated (non-dammed or non-diverted) streams with long-term gauge records. We found consistent evidence of decreasing discharge trends, increasing zero-flow days, and steeper downward discharge trends in smaller basins. Beyond directional trends, many systems have recently undergone shifts in flow state, including some streams that have transitioned from perennial to intermittent flow states. Our analyses provide evidence of stream drying consistent with climate change but also highlight knowledge gaps and challenges in empirically and statistically documenting flow regime shifts. We discuss the myriad consequences of losing flow and propose strategies for improving detection of and adapting to flow change.

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Stream drying has been observed throughout the world, shifting some systems from perennial (year-round) to intermittent (seasonal) flow regimes. The most prominent examples of river drying are due to dams and diversions in large, heavily regulated systems, such as the Colorado River in the US and the Nile River in Egypt (eg Gleick 2003). Stream drying can also occur in regions with highly exploited aquifers, such as in the arid southwestern US (eg Santa Cruz River; Webb and Betancourt 2014). These well-documented cases largely reflect heavily regulated systems losing perennial flow resulting from water extraction and anthropogenic demand for freshwater. In many cases, the ecological and societal consequences of flow shifts in these regulated systems are well understood and profound. Impacts include local and global extinctions of freshwater species, the collapse of fisheries and farming opportunities, and societal conflict over reduced water supplies (eg Coffel *et al*. 2019; Koehn *et al*. 2020).

In a nutshell:

- Climate change is expected to convert perennial streams (ie year-round flow) into intermittent ones (ie seasonal flow), contributing to biodiversity declines and loss of fisheries and water available for human use
- However, empirical evidence that novel climate-induced stream drying is occurring remains scarce
- We analyzed gauge records for minimally disturbed rivers in Mediterranean-climate regions and documented decreasing discharge trends as well as flow shifts, generally in a drier direction
- We discuss the challenges of detecting flow transitions and identify paths forward to better document and understand these potentially profound regime shifts for ecosystems and people

Beyond the direct effects of human activities on flow regimes, it is widely assumed that climate change will shift some perennial streams to an intermittent flow state (eg Larned *et al*. 2010; Schneider *et al*. 2013; Jaeger *et al*. 2014; Reynolds *et al*. 2015; IPCC 2022). Climate change is predicted to increase drought frequency and severity in many regions around the world, thus reducing surface flows in both regulated and unregulated streams (eg Beniston *et al*. 2007; Cayan *et al*. 2010; Dai 2011; Jaeger *et al*. 2014; IPCC 2022). Negative trends in flow over time have already been detected in many basins (eg Larned *et al*. 2010; Sabo 2014; Allen *et al*. 2019), and a recent global analysis of river flows suggests that some regions are drying consistently across the entire range of flow frequencies (Gudmundsson *et al*. 2021). The systems most vulnerable to shifts from perennial to intermittent flows tend to be low-order streams (Lowe and Likens 2005) and streams with low baseflows (Reynolds *et al*. 2015; Dhungel *et al*. 2016).

Climate-change–induced flow reductions in large basins may be buffered by inputs from large regional aquifers (eg Boulton and Hancock 2006), but flows in smaller basins and headwater

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streams are more tightly coupled to climate conditions (Lowe and Likens 2005; Reynolds *et al*. 2015; Dhungel *et al*. 2016). These smaller, unregulated stream systems compose the majority of the world's river network (~51–60% of the world's river miles; Messager *et al*. 2021) and are most likely to exhibit the impacts of climate change because they are not hydrologically connected to large aquifers (Garcia *et al*. 2017). However, low-order streams are also less likely to be monitored or gauged than larger systems (eg Krabbenhoft *et al*. 2022), suggesting limited ability to detect alterations in flow in the systems most likely to undergo such changes.

Despite widespread predictions of drying in small, unregulated streams, and the potential for profound consequences for local ecosystems (Panel 1; Figure 1) and people (Panel 2), few studies have documented flow regime shifts in such systems. In this study, we highlight examples of decreasing discharge trends and flow shifts in free-flowing Mediterranean-climate streams. We focus on the five recognized Mediterranean-climate regions because their rivers are characterized by extreme flow variability, including dry summers with low baseflows (eg Cid *et al*. 2017). Moreover, all five regions have experienced severe drought within the past decade, and droughts in these regions are expected to become more extreme and severe (IPCC 2022). In particular, we ask the following questions: (1) Is discharge trending downward generally across basins? (2) Are discharge trends similar across small and large basins? (3) Is the number of zero-flow days increasing generally in intermittent streams? And (4) beyond directional trends in discharge, is there evidence of flow regime shifts toward increased intermittency? In addition, we highlight key knowledge gaps and challenges to empirically and statistically documenting regime shifts from perennial to intermittent flow. Finally, we discuss methods for enhanced detection

Panel 1. Ecological effects of perennial to intermittent flow shifts in unregulated streams

Many studies have compared ecological communities in unregulated perennial versus intermittent streams (eg Datry *et al*. 2014), but far fewer have documented ecological changes caused by a *transition* from perennial to intermittent flow. Indeed, to our knowledge, the ecological impacts of climate-induced shifts from perennial to intermittent flows have only been closely studied in one system: a desert stream in the US state of Arizona. In this stream, notable changes in aquatic invertebrate community structure occurred following complete drying and transition from perennial to intermittent flow (Figure 1) (Bogan and Lytle 2011; Bogan *et al*. 2015). Surprisingly, species richness was similar before and after the transition to intermittent flow, but six species were extirpated, including the top predator, the largest shredder, and two flightless species. Taxa with rapid life cycles and strong dispersal abilities dominated under intermittent flows, because they were able to take advantage of shorter periods of time with water present. In the 17 years that have passed since the initial stream drying event, none of the extirpated taxa have returned to the system. Food web and ecosystem consequences were not quantified in this case, but other studies have shown that drying-induced losses of top predators cause trophic cascades that reduce primary productivity (eg Boersma *et al*. 2014). Additional long-term case studies are needed to better understand complex ecological processes set in motion by shifts from perennial to intermittent stream flow.

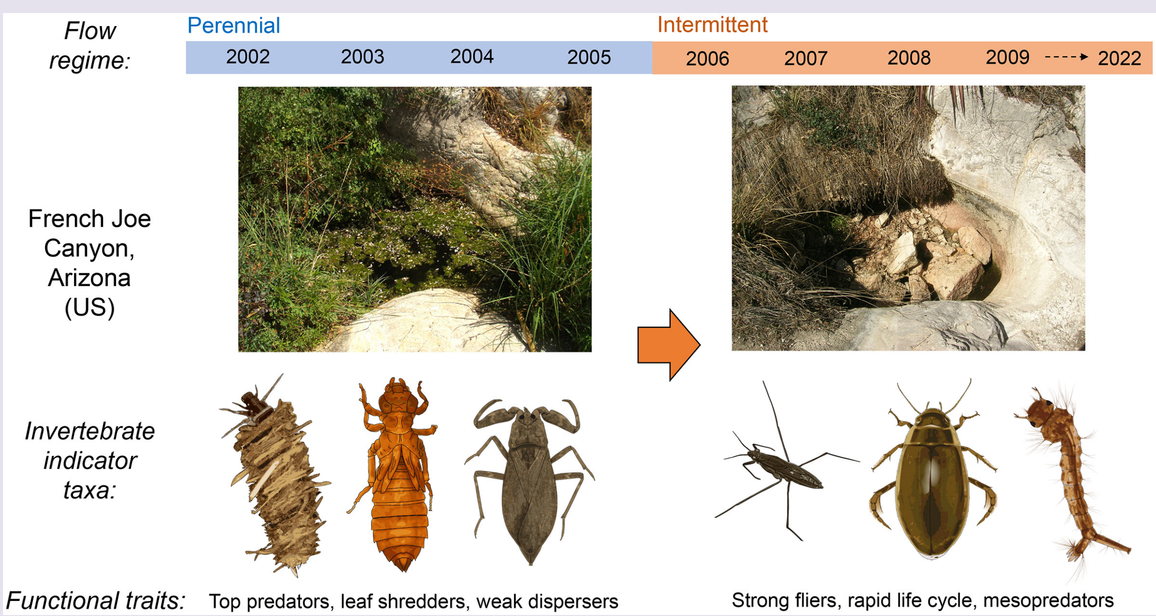

Figure 1. Changes in aquatic invertebrate taxonomic and functional trait composition before and after transition from perennial to intermittent flow conditions in a desert stream (Bogan and Lytle 2011). Invertebrate drawings courtesy of P Fortuño Estrada. Photo credits: MT Bogan.

Panel 2. Societal implications of climate-change–induced streamflow drying

Whether a stream is perennial or intermittent affects its potential to serve as municipal or agricultural water source, and its cultural or recreational uses, among other uses. Furthermore, how societies perceive and interact with perennial versus intermittent streams can affect the way in which the surrounding landscape is managed. In addition, in many regions, environmental laws may no longer apply to a stream if it loses perennial flow; this designation is an active and contentious legal issue in many parts of the world, including the US and Europe (Fritz *et al*. 2017; Marshall *et al*. 2018).

In small, unregulated basins, declining flow and flow shifts could reduce the amount of water available for people. Indeed, small, headwater streams contribute disproportionately to drinking water supply. In the US, for example, 58% of streams providing surface-water intakes that supply public drinking water are headwater, intermittent, or ephemeral streams (EPA 2017). Therefore, the decreasing discharge trends documented here (Figure 2) have implications for water security. Moreover, flow shifts (Figure 3) can exacerbate the issue. When streams that feed municipal aquifers go dry seasonally, utilities must find additional sources of water or reduce water deliveries to households and businesses (Richter *et al*. 2013). When surface-water supplies are limited, groundwater pumping is also likely to increase, potentially accelerating stream drying in nearby surface waters (Turner and Richter 2011).

Stream drying also has the potential to decrease the cultural, recreational, and economic activities associated with flowing streams, including swimming, fishing, plant harvest, boating, and contemplation of flowing waters. Loss of riverine species due to stream drying reduces opportunities to engage in cultural practices and consume traditional foods, leading to poorer health outcomes and reductions in community well-being, especially among Indigenous communities. Recreation economies centered on fishing, swimming, and rafting also rely on perennial flow. The aesthetic qualities of flowing rivers contribute to people's desire to engage in recreational activities on rivers. Many people find intermittent or ephemeral streams to be less aesthetically pleasing and less ecologically valuable than flowing waters (Rodríguez-Lozano *et al*. 2020), although over time people may adapt their recreational and aesthetic preferences to novel ecosystems within intermittent or dry streams.

Panel 3. The many drivers of flow regime shifts: regional and local complexities

In some cases, the cause of flow regime change is directly related to land and/or water use, including dam construction and large-scale groundwater pumping. In contrast, flow change in basins with little anthropogenic use can be assumed to be climate driven (Figures 2 and 3). Most river basins, however, are affected at least to some degree by human activities, and their stream flow regimes are controlled by the complex interactions of land use, water use, and climate. For example, Allen *et al*. (2019) reported long-term declines in the spatial extent of perennial streams in Arizona, but the effects of climate could not be distinguished from the influences of regional surface- and groundwater withdrawals. When surface-water availability declines due to climate change, local inhabitants may increase pumping of groundwater, increasing potential for both direct and indirect effects of climate change on streamflow.

In addition to the direct impacts of climate change (ie less precipitation and increased temperatures, as is expected to occur in Mediterranean-climate regions) on flow, indirect effects can be very complex and difficult to track. For example, in upland ecosystems, climate change is causing tree mortality and plant community transitions that alter transpiration rates and may affect streamflow locally (McLaughlin *et al*. 2017). Similarly, the increased extent and intensity of wildfires due to climate change can alter both infiltration and transpiration rates, leading to either increased or decreased stream flow depending on local geology and climate (eg Hallema *et al*. 2017). Further interdisciplinary research is needed to quantify the direct and indirect effects of climate change on streamflow, as well as how climate-induced changes in upland ecosystems can alter streamflow downslope.

Finally, although we focused on river drying, it is important to acknowledge that river perennialization—or shifts from intermittent to perennial flow regimes—are also widespread. Indeed, we detected evidence of *decreased* intermittency in some streams, particularly in Spain and South Africa (Figure 2). River perennialization can be driven by multiple factors, including river regulation, return flows from agriculture, urban runoff, and the release of treated wastewater, among others (summarized in Chiu *et al*. [2017]). River perennialization may also result from climate change, with increased low, mean, and high flows due to regionally wetter climates (Gudmundsson *et al*. 2021).

of flow regime shifts and strategies to adapt to these changes. We acknowledge that flow regime alteration is a global phenomenon that affects all stream types (Döll *et al*. 2009), including intermittent streams (Zipper *et al*. 2021), and that disentangling the effects of climate versus the impacts of other anthropogenic activities on flow regimes is difficult (Panel 3). Here, however, we focus exclusively on unregulated streams in Mediterranean-climate regions that are at risk of losing flow mainly because of climate change.

Are free-flowing Mediterranean-climate streams losing flow?

To document flow change, we compiled gauge records from the five Mediterranean-climate regions of the world, including California (US), Chile, South Africa, Spain, and Western Australia. For each gauge, we first downloaded daily discharge records from public sources (see Appendix S1: Panel S3) and then limited our analysis to gauges located in

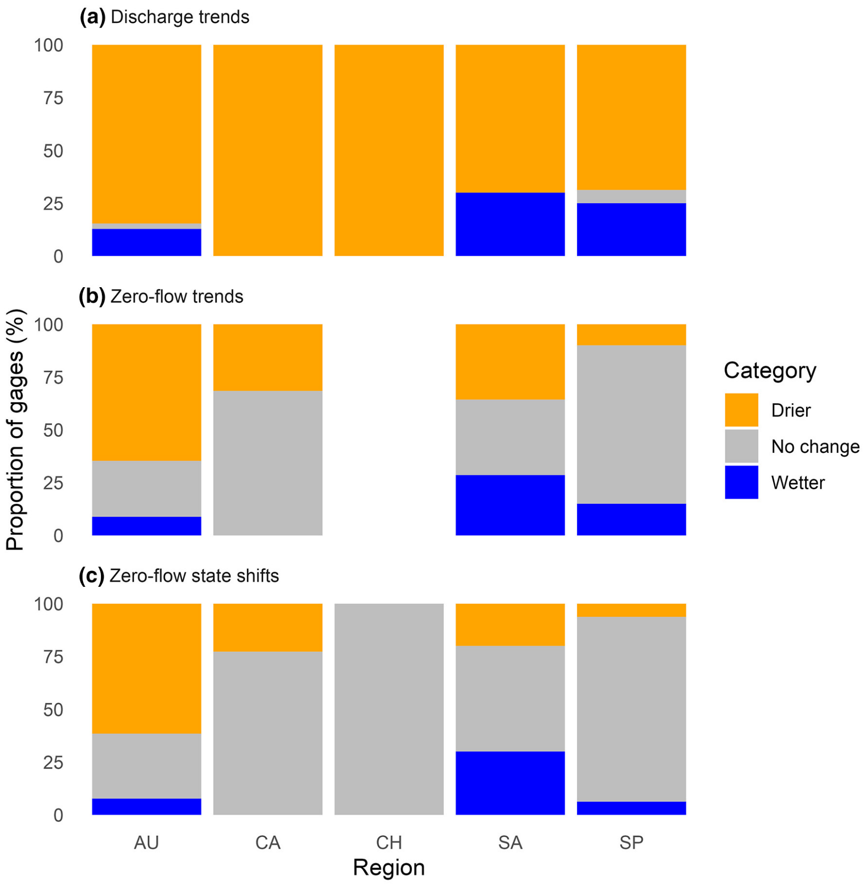

Figure 2. Summary of flow trends and state shifts for each of the five Mediterranean-climate regions (AU: Australia, CA: California, CH: Chile, SA: South Africa, SP: Spain), including trends in (a) daily discharge and (b) zero-flow days. Chile was excluded from the zero-flow trend analysis because all seven of the streams from that country were identified as perennial streams. Beyond discharge trends, we also found that many systems show evidence of flow state shifts (c), largely toward a greater number of zero-flow days (that is, increased intermittency).

Mediterranean-climates zones by retaining the subset of gauges located in the Köppen-Geiger climate classes Csa (temperate with dry, hot summers), Csb (temperate with dry, warm summers), and Csc (temperate with dry, cool summers)—that is, areas with a dry summer—using maps from Beck *et al.* (2018). Next, we identified gauges located in minimally disturbed basins. In the US and Australia, we used "reference" gauges identified by the US Geological Survey (USGS) and the Australian Bureau of Meteorology, respectively. In South Africa, Chile, and Spain—where reference gauges have not been designated by agencies—we instead relied on aerial image analysis of upstream watershed conditions to identify basins with no evidence of major reservoirs or large water-related infrastructure projects. Our determination of "reference-quality" gauges in Spain (excluding Catalonia) is consistent with that proposed by Messager *et al.* (2021). Third, we identified gauges with daily data from 1980 to 2019 (ie the most recent 40 years in common across the five regions) and no more than 1 year of missing data.

Overall, we identified 158 gauges that met our criteria for inclusion (ie Mediterranean-climate, reference-quality, 40 years of data from 1980 to 2019, and no more than 1 year of missing data; Appendix S1: Panel S1 and Figure S1). To reduce noise in zero-flow conditions, we defined "zero flows" as flows < 0.1 cubic feet per second (cfs). Finally, for our analysis of zero-flow trends, we used a liberal definition of "intermittent" and included the subset of streams with greater than or equal to 1 day per year of zero-flow on average (ie ≥40 days across the 40-year study, following Messager *et al.* [2021]).

Discharge and zero-flow trends

Using the population of gauges that met our criteria for inclusion, we conducted trend analyses on daily discharge (for each gauge in our population) and on the annual number of zero-flow days (for the subset of intermittent gauges) across the time-series by means of nonparametric Mann-Kendall tests. We found consistent evidence of negative trends in discharge in the study regions (Figure 2a). In addition, we observed a globally significant, positive correlation between Mann-Kendall trend in discharge and drainage area, implying stronger declining trends in smaller watersheds ($P < 0.001$, $r = 0.13$), although the strength of the relationship varied across regions (Appendix S1: Figure S2). We also found that the number of zero-flow days is generally increasing, particularly in Mediterranean-climate regions of Australia and California (Figure 2b). However, in South Africa and Spain there were similar numbers of streams with increasing zero-flow days and decreasing zero-flow days (Figure 2b). Chile was excluded from the zero-flow trend analysis because all gauges in our population for that country were identified as perennial.

Flow shifts

We next explored evidence of flow regime shifts. Specifically, we conducted a breakpoint analysis on the zero-flow days per year using the *strucchange* package in R. We constrained the analysis to test for evidence of a maximum of one breakpoint (indicating a state shift). We found widespread evidence of flow state shifts; 53 of 158 gauge records exhibited evidence of a state shift, including in four of five regions. The vast majority (77%, $n = 41$) of flow shifts were toward drier conditions (Figure 2c), including several instances of streams that were formerly perennial but are now intermittent (Figure 3).

Overall, these results provide evidence of declining flows and shifting flow regimes in unregulated streams, which likely

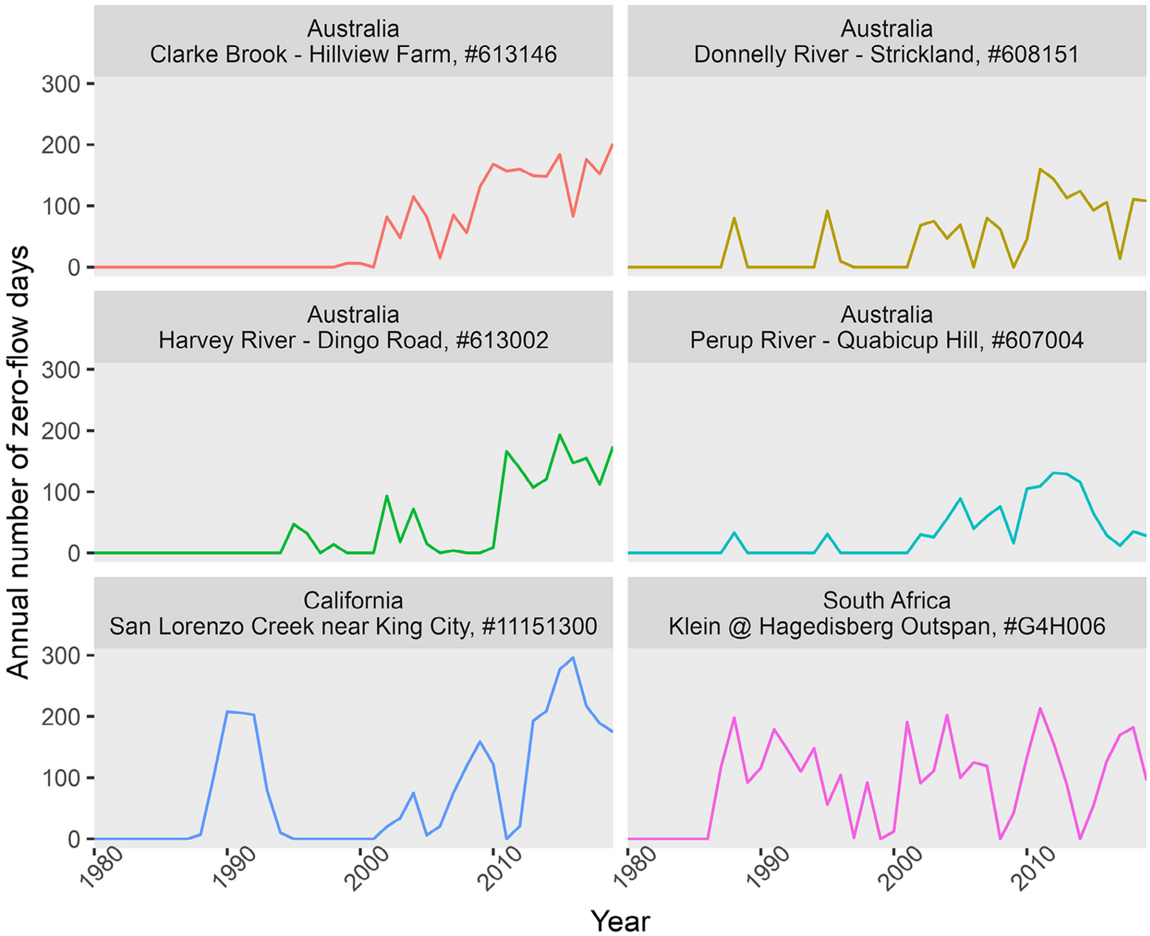

Figure 3. Six examples of perennial to intermittent flow shifts from free-flowing Mediterranean-climate streams—all from the larger pool of gauges showing evidence of a flow state shift (see Figure 2c). Note that these six examples are simply a subset of gauges that both (i) shifted in flow state and (ii) started with few to no zero-flow days before the flow shift (ie when the streams were perennial).

can be attributed to changes in regional climate (eg climate-driven increases in temperature and evaporative demands and changes in precipitation patterns). Less clear, however, is how commonly flow shifts are occurring in ungauged streams. This knowledge gap reflects a suite of challenges associated with monitoring and detecting flow shifts.

Detection challenges

We found that Mediterranean-climate streams with declining discharge trends tended to occur in smaller drainage basins. Previous research has emphasized that low-order streams are among those most likely to shift to an intermittent regime (eg Dhungel *et al*. 2016). However, low-order streams are underrepresented in existing gauge networks (eg Krabbenhoft *et al*. 2022) and those gauges are disproportionately at risk of being deactivated (Figure 4). This creates a challenge for detecting river drying and highlights the need to diversify approaches for capturing such regime changes.

In addition, with respect to measuring low flows in streams, there are fundamental challenges that complicate the detection of flow cessation timing. For one, it is difficult to obtain a reliable flow measurement in natural stream channels at very low flows using standard methods (Rantz 1982). Furthermore, the river stage at which zero flow occurs is often extrapolated from a rating curve that is created by measurements collected at times of much higher flow conditions, creating uncertainty in zero-flow records. For example, unusually high numbers of very low (but not zero) values may indicate that zero readings were recorded as a limit of detection rather than as a true zero. Similarly, increases in measurement precision through time in multidecadal records could lead to incorrect inferences about change in zero-flow conditions, particularly in small, low-flow but perennial systems.

Even when reliable gauge data exist, measurements of zero flow do not always provide information about stream channel drying. Gauges are designed to measure changes in streamflow over time at a single location. The spatial dimensions of stream drying have received less attention, although this is beginning to change. Indeed, a suite of approaches are now available to study the spatial extent of drying, through direct observations of the extent of wetted habitat via wet/dry mapping (eg Allen *et al*. 2019) or through the use of sensors (eg temperature, electrical-resistivity, photograph, and/or video)

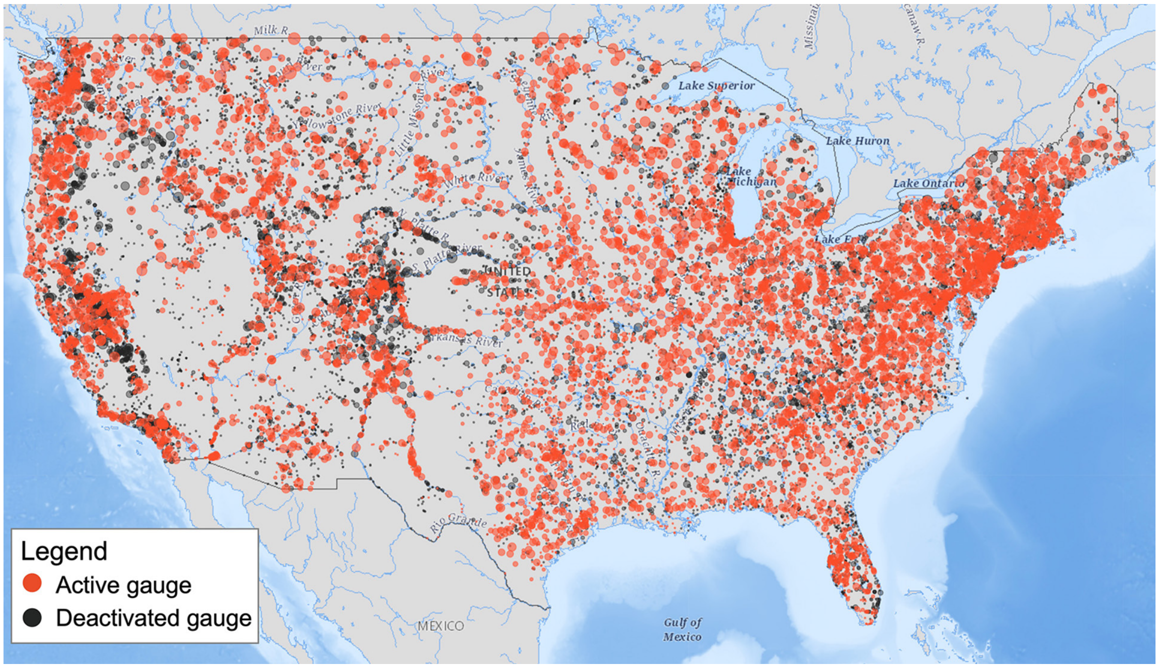

Figure 4. Distribution of all US Geological Survey gauges across the conterminous US. Red circles indicate active gauges as of 2016 (n = 7985) and black circles indicate gauges that were deactivated but had recorded at some point in the past (n = 14,424). Circle size represents gauging record length. Notably, we found that gauge stations with decreased monitoring intensity were differentially located in smaller drainages (Welch two-sample t test, t = 4.21, $P = 2.57 \times 10^{-5}$; see Appendix S1: Panel S2 for details about the analysis). Adapted from Ruhí *et al.* (2018).

to determine the presence or absence of water (eg Jaeger and Olden 2012).

Statistical challenges

Even if streamflow is monitored adequately, it can be challenging to decide whether a string of zero-flow readings constitutes a flow regime shift. Many approaches exist for defining stream intermittency, including some that combine different dimensions (eg flow magnitude, duration of zero-flow spell within years, frequency of zero-flow observations across years). Regardless, variation in the length of the time-series influences our ability to detect change. For instance, most stream gauges in the US have been in operation for less than 30 years (Ruhí *et al.* 2018). Thus, the effects of climate fluctuations versus a drier "new normal" may be difficult to disentangle (Poff 2018). Studying the distribution of flow anomalies via spectral analysis (eg Wu *et al.* 2015) may help, given that supra-seasonal and/or multiyear droughts have some associated periodicity (eg El Niño–Southern Oscillation, Pacific Decadal Oscillation). Zero-flow values that are still anomalous after accounting for these supra-seasonal cycles may indicate a regime shift. However, detecting important seasonal cycles based on daily data still requires relatively long periods of record (typically 20 years or more; Sabo and Post 2008).

The path forward

Here we document declining discharge in Mediterranean-climate streams (Figure 2), including an increase in the number of zero-flow days in intermittent systems and flow shifts toward increased intermittency (Figures 2 and 3). Other examples of flow shifts almost certainly exist (eg Figure 1). However, because of the empirical and statistical challenges discussed above, such flow shifts are difficult to document, and disproportionate gauge retirement in the small basins vulnerable to flow regime change only exacerbates the problem (Figure 4). Moreover, other systems where intermittency is well documented and attributed to human water use may also be responding to climate change, but the climate signal is obscured (eg Fritz *et al.* 2008). In short, scientists recognize that they are not effectively monitoring these potentially profound changes to stream ecosystems, so the question remains: how can detection be improved? Below we highlight actions for better documenting flow regime change and understanding and mitigating its consequences.

Preserve and expand streamflow monitoring networks

Preserving and expanding streamflow monitoring networks will require identifying gauges in low-order streams that are most at risk of deactivation and ensuring that funding for maintenance and operations is sustained into the future. The reactivation of historical gauging stations and installation of new gauges should also be supported, and could be a way to address current biases in gauge placement (Krabbenhoft *et al.* 2022). Stream gauges require substantial investment for installation and maintenance (eg Normand 2021). However, there are also opportunities to expand stream monitoring networks through more cost-effective sensor technologies, remote sensing (drone- and satellite-based), and community-driven science, including wet/dry mapping (eg fine-scale drying data; Allen *et al*. 2019) and crowd-sourced stream observation data via smartphone apps (eg CrowdWater, Anecdata; Kampf *et al*. 2018). Expanding the spatial extent and temporal frequency of stream observations will enhance our ability to identify and understand the contexts in which stream drying occurs. To ensure that data are accessible, we echo the recent call of Jaeger *et al*. (2021) for the development of national and international repositories of streamflow presence data as a necessity for improved understanding of the duration and frequency of surface flows across the globe.

Leverage biomonitoring data to enhance detection

Biomonitoring data offer another promising source of information to detect stream drying (eg Fritz *et al*. 2008). There is considerable potential for ecological indicators to detect flow regime change. Applying this approach requires understanding the consequences of flow characteristics on aquatic community composition or traits (Figure 1). However, many of the same limitations of flow gauge site selection and representation of small streams also apply to biomonitoring programs, including spatial biases toward larger streams and urban centers. Nevertheless, biomonitoring programs that employ a probabilistic sampling design, with random coverage of headwater, low-order, and potentially intermittent sites, should make it possible for detecting flow regime change depending on the sampling frequency and length of record. We also recommend that biomonitoring organizations identify and support "sentinel" monitoring locations that are paired with flow gauges and distributed throughout a network and that include sites most likely to shift in flow state (eg Reynolds *et al*. 2015; Dhungel *et al*. 2016).

Promote long-term studies

We could identify only a single empirical study that documented the ecological consequences of a shift from perennial to intermittent flow (Panel 1). Sudden species losses can have lagged effects on community and ecosystem dynamics, suggesting the need for additional long-term studies to better understand complex ecological processes set in motion by flow regime shifts.

Enhance interdisciplinary collaboration

Increasing collaboration among scientists in different research fields will help to improve understanding and prediction of climate-induced changes in the timing and spatial extent of seasonal low flows and drying along with their ecological consequences. "Critical zone" science integrates geomorphic, hydrologic, biogeochemical, and ecological approaches to explore questions about the complex interactions of rock, soil, water, air, and living organisms in the thin veneer of the Earth extending from the top of the canopy through the soil and weathered bedrock. This multidisciplinary and highly integrative field relies on diverse tools and approaches and a network of critical zone observatories that has considerable relevance for the study of intermittent streams (Fovet *et al*. 2021).

Coordinate cross-scale multi-method research efforts

To study stream drying, groundwater withdrawals, patterns of wetted habitat availability, and ecological consequences will require better coordination among organizations and the use of different methods across different scales. For example, during the drought event that resulted in a marked restructuring of the aquatic invertebrate community documented by one of the authors of the present study (Panel 1), a major citizen-science effort to map wetted habitat was occurring in another part of the same basin (Turner and Richter 2011). The two efforts were uncoordinated and employed different approaches; the upstream effort monitored the aquatic invertebrate community and deduced a flow shift based on the marked and persistent change to the aquatic community, whereas the downstream effort documented the contraction of wetted habitat. This example highlights the potential to coordinate studies within basins and among river scientists and community members to better understand network scale patterns of flow permanence and ecological consequences at different scales and locations in the network.

Employ management actions to help prevent or mitigate loss of flow

Strategies that are being used to enhance streamflows in the arid and semi-arid regions of the world can also help prevent or mitigate the loss of perennial flow. For instance, watershed management activities, including forest thinning and prescribed burns to mitigate wildfire risk, also reduce summer evapotranspiration (Butsic *et al*. 2017) and may play a role in increasing dry season baseflows. Many watersheds have lost their water-holding capacity as a result of urbanization, logging, and intensive agriculture. Restoration actions that slow precipitation runoff, promote infiltration, and enhance temporary storage in wetlands across the landscape can help to buffer climate-induced stream drying. For example, beaver (*Castor canadensis*) dams and human-built analogs are being deployed in western North America to capture and store runoff and attenuate drying. Policies that reduce ground- and surface-water diversions for human use are also increasingly used to enhance flows to benefit threatened and endangered fishes. Better understanding of intermittency risk could aid environmental agencies and local communities in determining the most appropriate management actions for their local environmental and social setting.

Clarify flow regime classifications and legal protections for systems undergoing flow regime change

Finally, knowing whether a stream is perennial often influences whether certain environmental laws apply to that water body, and consequently this designation is an active and contentious legal issue in many parts of the world (eg Fritz *et al.* 2017; Marshall *et al.* 2018). How existing regulations will handle flow regime *change* is unclear, and clarity and consensus on what constitutes a flow regime shift are also needed (eg will newly intermittent systems continue to be intermittent during unusually wet periods?). More generally, the issue of shifting flow regimes highlights the challenges of protecting streams in a non-stationary world.

Conclusions

Climate change is widely anticipated to contribute to river drying, with important consequences for ecosystems (Panel 1) and society (Panel 2), and we provide evidence that this is already happening in small, minimally disturbed basins (Figures 2 and 3). Although we focused on river drying in Mediterranean-climate systems because of their characteristic seasonality and sensitivity to climate change, flow shifts are almost certainly happening in other climate regions as well. Indeed, the only study we are aware of documenting ecological consequences of a shift from perennial to intermittent flow was conducted in a desert stream in the US Southwest (Panel 1). In addition, we show that gauges in small drainages are more likely to be retired (Figure 4; Appendix S1: Panel S2), which, combined with the fact that these are also much less represented in the gauge network, suggests a decreasing capacity to detect flow regime change in the very systems that are most likely to experience shifts in flow states. There is considerable potential to preserve and expand monitoring efforts, to promote coordinated studies using transdisciplinary methods, and to better coordinate among entities monitoring in different regions to improve our understanding of systems undergoing flow regime change. This will require substantial investments of time and financial resources but is essential to guide management and policy actions for mitigating and adapting to climate-induced flow regime change.

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Data Availability Statement

Please see Appendix S1: Panel S3 for an extended statement about the data used in this study.

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