STREAMFLOWS

# Ephemeral stream water contributions to United States drainage networks

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**Ephemeral streams flow only in direct response to precipitation and are ubiquitous landscape features. However, little is known about their influence on downstream rivers. Here, we modeled ephemeral stream water contributions to the contiguous United States network of more than 20 million rivers, lakes, and reservoirs, finding that ephemeral streams contribute, on average, 55% of the discharge exported from regional river systems, as defined by the United States Geological Survey. Our results show that ephemeral connectivity is a substantial pathway through which water and associated nutrients and pollution may enter the perennial drainage network and influence water quality. We provide quantitative insight into the implications of differing interpretations of regulatory jurisdiction under the United States Clean Water Act, including the current standard adopted by the Supreme Court of the United States in 2023.**

Streams transport nutrients, sediments, pollutants, and other solutes from the land surface to rivers, lakes, reservoirs, and ultimately the oceans (*1*–*5*), influencing all downstream water quality (*6*, *7*). The most upland streams (hereafter "headwaters") are often "ephemeral" streams, which flow only in direct response to precipitation and are disconnected from groundwater year-round, unlike intermittent rivers, which are seasonally connected to groundwater (ephemeral streams "fill up," whereas intermittent streams "run dry"). When combined, nonperennial streams (ephemeral and intermittent) account for more than half of the global river network (*8*). Although much recent work has developed classification models to map nonperennial stream extent (*8*–*14*), there is little similar research focusing specifically on ephemeral streams (*12*, *15*, *16*), and all work stops short of assessing the hydrological contributions of nonperennial streams to the overall drainage network at broad spatial scales. It is well established that headwater streams contribute meaningfully to downstream water quantity and quality regionally (*17*, *18*), but we presently have no explicit assessment of ephemeral contributions to global hydrology or their potential influence on downstream water quality.

In this context, we developed a model to quantify ephemeral stream contributions to river systems, defined as the percentage of river water that enters the river system through an upstream ephemeral catchment under mean annual conditions. The model is underpinned by a simple theory: Because ephemeral streams flow only in direct response to rainfall, they must be perched above the water table over the entire year. To distinguish ephemeral streams from intermittent rivers, we first compared modeled long-term monthly water table depths (*19*, *20*) with predicted bankfull depths (*21*) in 20,708,899 discrete streams, rivers, lakes, reservoirs, canals, and ditches across the contiguous US (CONUS) (*22*). Any stream channel where the water table remains deeper than the bankfull depth across all 12 months is considered ephemeral (fig. S1). Then, we route through the river systems using a published river-lake-reservoir routing framework (*23*) to ensure that the newly mapped ephemeral channels are not immediately downstream of perennial rivers, per theory. We validate the resulting ephemeral stream map using 7207 in situ site assessments (see the supplementary materials). Finally, with map in hand, we use a published streamflow model (*22*) described in the supplementary materials and our routing framework (*23*) to quantify the fraction of every CONUS river's mean annual discharge that was contributed by upstream ephemeral catchments. In other words, we follow water as it moves downstream (a Lagrangian framing) and keep track of its downstream dilution by larger and larger perennial rivers. We define our river systems using the US Geological Survey (USGS) level-four (HUC4) drainage basins in their hydrologic unit code (HUC) scheme, keeping track of when a river system flows into a downstream system. These river systems are hereafter referred to as "drainage networks." See figs. S1 to S3 for overview flowcharts of the model and its validation. See supplementary materials section S1 and figs. S4 to S15 for the results of the validation, sensitivity, and uncertainty tests performed at a combined >10,000 in situ sites. By leveraging a parsimonious modeling approach, our goal is not simply to show that ephemeral streams occur, but also to elucidate how their prevalence shapes the hydrology of rivers many kilometers downstream.

Our scientific findings speak directly to the ongoing debate surrounding the jurisdictional scope of the US Clean Water Act (CWA) and whether it applies to ephemeral streams. The CWA grants federal agencies the authori regulate the "Waters of the United Sta (WOTUS) in order "to restore and maintain the chemical, physical, and biological integrity of the Nation's waters" (*24*). Although there is general agreement that WOTUS includes large interstate waterways characterized as "navigable waters," differing and conflicting interpretations apply to wetlands and smaller and/or tributary interconnected waterways, especially those that are ephemeral (*25*, *26*). For many years, no majority Supreme Court opinion controlled the scope of WOTUS, leaving regulators to navigate among competing definitions such as waters that are "inseparably bound up" with navigable waters (*27*), waters that hold a "significant nexus" with navigable waters (*28*), and—most narrowly—waters that are "relatively permanent, standing or continuously flowing bodies of water" (*28*). In the past decade alone, federal agencies under three administrations all promulgated rules with differing definitions of the CWA's jurisdictional scope, including one that explicitly excluded ephemeral streams from federal coverage (*29*–*31*). The issue was addressed once again by the Supreme Court in the 2023 case of *Sackett* v. *Environmental Protection Agency* (EPA), where a majority of the Court narrowly defined WOTUS as encompassing "only those relatively permanent, standing or continuously flowing bodies of water forming geographical features that are described in ordinary parlance as streams, oceans, rivers, and lakes" (*32*) and effectively removing ephemeral streams from US federal jurisdiction. Recently, deep learning was used to predict what fraction of CONUS waters are regulated under these different interpretations of the CWA by mapping and quantifying the spatial footprint of regulation (*14*), similar to previous work (*8*–*13*). We too provide mapping of ephemeral streams but specifically focus on the magnitude of water that ephemeral streams contribute to river systems. We provide new results for both the scientific and regulatory communities that enrich mapping efforts and may help in establishing the importance of ephemeral streams to water quality science and regulation.

## The ephemeral pulse of drainage networks

On average across CONUS basins, we predict that 55% of annual discharge exported from HUC4 drainage networks is sourced from upstream ephemeral streams (Fig. 1A). This means that, on average, most of the streamflow in the large, mainstem rivers of these networks (defined by HUC4 basins) is contributed by upstream ephemeral catchments. Mainstem rivers are often "navigable waters" and thus fall under CWA regulation. For example, 51% of the Mississippi River export originated in ephemeral catchments, and Columbia River export is similar at 52% ephemeral. This result

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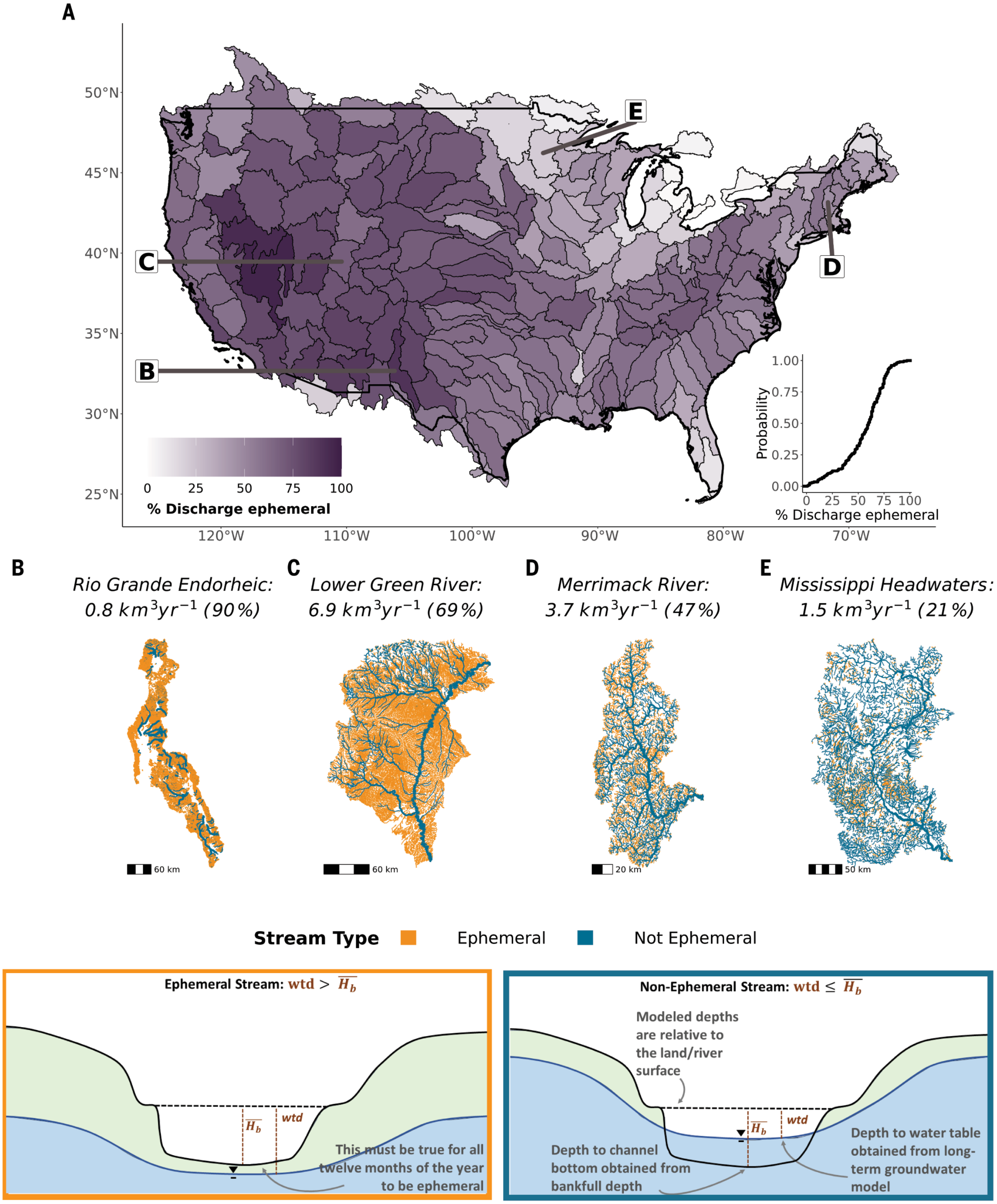

**Fig. 1. Ephemeral stream water contributions to CONUS drainage networks.** (**A**) CONUS map of the percentage of discharge exported from drainage networks that is ephemerally sourced (see the supplementary materials, equation S1). Inset shows the empirical cumulative distribution function of the basins. (**B** to **E**) Drainage network maps and ephemeral export percents for four representative basins: an endorheic desert basin (B), an arid western basin (C), a temperate mountainous basin (D), and a temperate flat basin (E). For (B) to (E), reach width corresponds to the size of the river (specifically, the logarithmic bins of discharge relative to map scale). For each basin, we also provide the modeled mean annual volume of exported water that is ephemerally sourced. All 205 basins are mapped in figs. S16 to S28. At the bottom are graphical insets describing how we identify ephemeral streams (see the supplementary materials).

varies substantially across basins (from 1 to 97%), with generally greater ephemeral influence in basins west of the Mississippi River. Hereafter, we refer to this region as "West," with basins east of the Mississippi River referred to as "East." Regional hotspots occur where ephemeral streams most dominate the landscape, namely the desert and endorheic basins of the Southwest and Great Basin (Fig. 1 and figs. S16 to S28). However, ephemeral contributions to discharge are consistently high across CONUS: 68% of networks export water that is at least

50% ephemeral. We also express the ephemeral contribution to discharge as a function of drainage area (see the supplementary materials, equation S2), where on average across basins, 58% of a basin's upstream drainage area is ephemeral and there is an east-west divide in land surface contributions to drainage networks (fig. S29). Given that water generally accumulates in drainage networks that follow predictable scaling patterns (*17*, *33*–*36*), our results (Fig. 1A) are theoretically anticipated by the average upstream ephemeral network extent (fig. S4C and supplementary materials section S1). Our results also agree with previous modeling in the northeastern US where 70% of exported discharge is sourced from headwater streams regardless of their ephemerality (*17*).

Our results are dependent on the scale of the drainage networks. Our goal is to explore the influence of ephemeral streams on major navigable rivers many kilometers away from the headwaters but still at a regionally meaningful scale. If we ran our analysis on the >100,000 smallest HUC basins (HUC12), ephemeral contributions would be high, whereas the 18 basins at the largest size (HUC2) would aggregate too many rivers to show meaningful patterns. Therefore, we chose to run our analysis using HUC4 basins, which colloquially correspond to "subregional" drainage basins and generally contain one or two primary, mainstem rivers. This is a compromise between larger basins, in which too many mainstem rivers would make it difficult to isolate the ephemeral contributions to individual networks, and smaller basins, which would be limited exclusively to small streams and tell us little about the influence on downstream navigable waters. For reference, the HUC4 basins used in this analysis have a median of eight stream orders and a median mainstem discharge of 286 $m^3$/s. These include, for example, the Willamette, Connecticut, Sacramento, and Suwannee rivers, and it is on these major navigable waters that we find a mean 55% contribution from ephemeral streams.

Ephemeral stream hydrography (Fig. 1, B to E, and figs. S16 to S28) is largely governed by lateral groundwater fluxes and watershed geomorphology and is a result of both topography and climate (*37*, *38*). In the East, ephemeral streams are most numerous in upland settings, where they sit upslope of the groundwater point of emergence (e.g., Fig. 1, D and E). In much of the West, where the water table is kilometers below the surface, ephemeral streams can dominate the landscape (Fig. 1, B and C). The Great Lakes/upper Midwest region and Florida have the smallest ephemeral influence due to low-order networks with persistently shallow water tables (*20*). The Midwest region is also strongly influenced by artificial irrigation ditches, which are not natural ephemeral streams but contribute meaningfully to annual discharge. Their contributions dilute the ephemeral influence on discharge exported from the drainage networks.

Internal to drainage networks, we show that stream size exerts a fundamental control on the ephemeral contribution to downstream hydrology (Fig. 2). Median first-order discharge is, on average across basins, 79% ephemerally

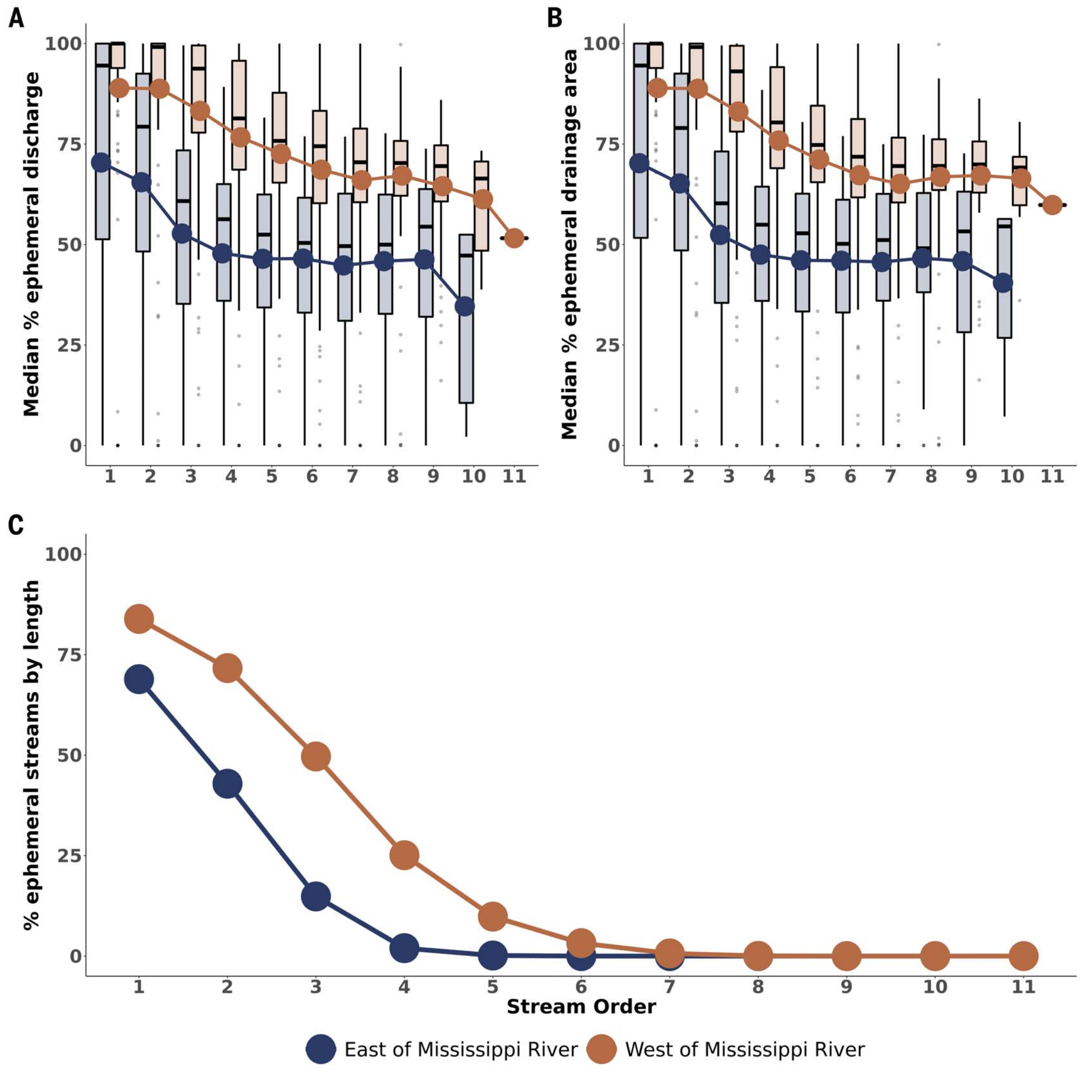

**Fig. 2. Ephemeral stream water contributions by river size.** (**A**) Median percentage of discharge that is ephemerally sourced by stream order, where Tukey-style boxplots are composed of the 205 CONUS basins and show distributions using boxes [the 25th to 75th percentiles or the interquartile range (IQR)], whisker lines (1.5 times the IQR), and outlier points (higher or lower than 1.5 times the IQR). Points and lines in (A) and (B) are the stream order means across CONUS basins. (**B**) Same as (A) but for the median percentage of upstream drainage area that is ephemeral. (**C**) Percentage of total network length that is ephemeral. Note that only one network, the lower Columbia River, has 11 stream orders. Stream orders are relative to the resolution of hydrography and cannot be directly compared across river network datasets. See the supplementary materials for the source data behind these stream orders.

sourced (Fig. 2A, points and lines). This result varies predictably for basins east and west of the Mississippi River (70 versus 89%, respectively) and by physiographic region (fig. S30). Given the first-order control of topography on eastern ephemeral stream presence (Fig. 1), the eastern ephemeral contribution decreases rapidly to ~50% by the fourth stream order, whereas in western basins, it decreases more slowly with stream size (Fig. 2A). The ephemeral drainage area percentage decreases similarly with stream size (Fig. 2B). The average ephemeral influence is notably skewed from the median ephemeral influence, highlighting the influence of outlier basins (and in particular, basins with many international streams that lower the basin's CONUS ephemeral contribution; see next paragraph). Overall, these results are driven by the sheer extent of ephemeral streams in orders 1 to 3 in the East and 1 to 5 in the West (Fig. 2C). Despite flowing infrequently (Fig. 3), the extent of the cu1mulative ephemeral river network means that they contribute a substantial portion of annual streamflow. Our results and river network scaling theory imply that nonperennial rivers, which make up more than half of the global river network (*8*), are likely predominately ephemeral streams rather than intermittently dry rivers.

While we model every river that flows into CONUS, we limit our ephemeral stream classification to CONUS ephemeral streams because Mexican and Canadian rivers (as well as any

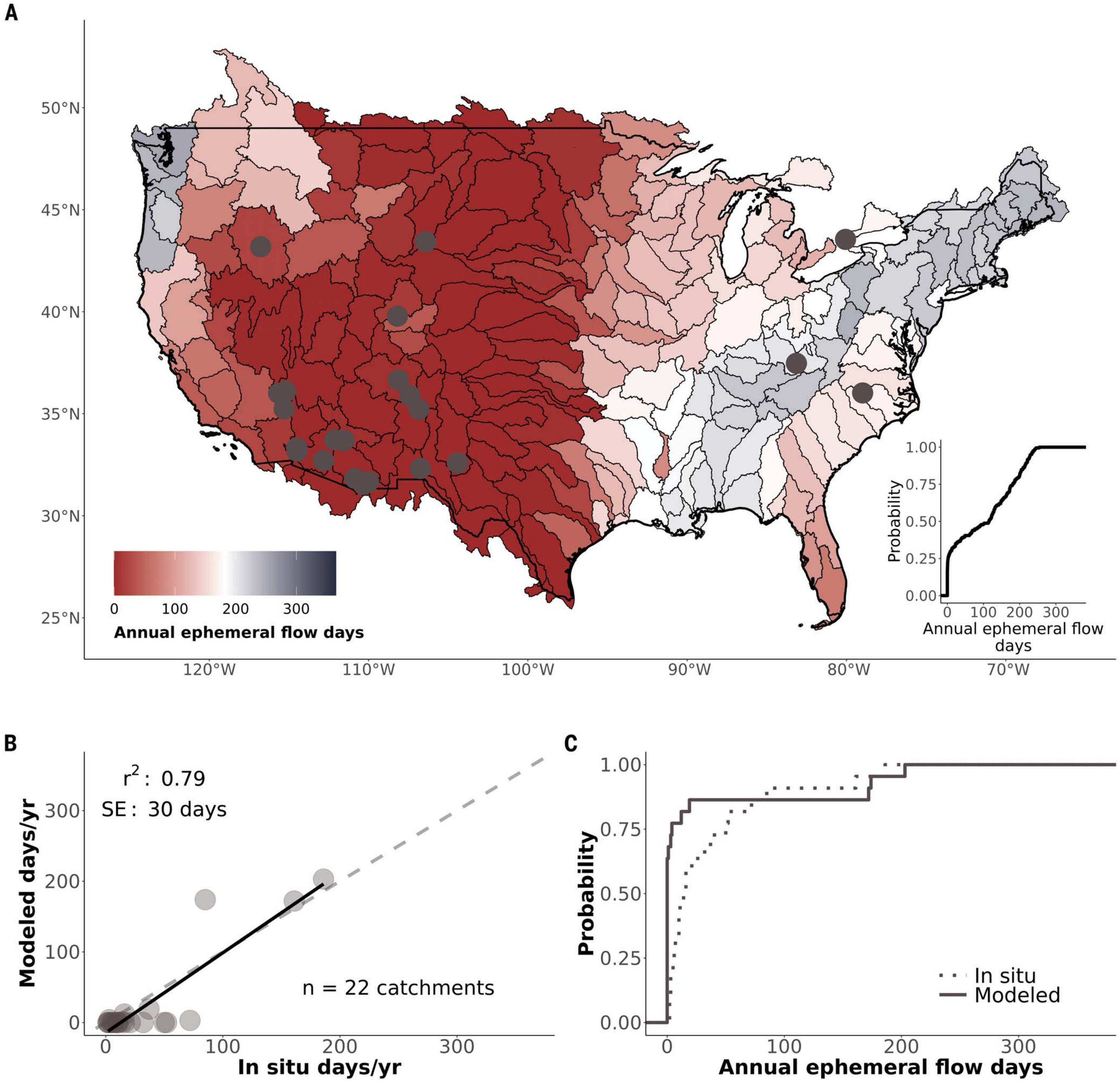

**Fig. 3. How often ephemeral streams flow.** (**A**) CONUS map of the predicted basin-average number of days that ephemeral streams flow per year. Inset shows the empirical cumulative distribution function of the basins. Gray points indicate approximate locations of field verification data. (**B**) Field verification of model results. The black line is the linear regression between predicted and measured values. SE refers to the regression standard error and $r^2$ refers to the coefficient of determination. (**C**) Field verification by empirical cumulative distribution functions for the in situ and modeled values from (B).

canals, ditches, and ponds) fall under different water quality regulation rules. We also do not account for human groundwater pumping (see the supplementary materials), which lowers water tables and likely results in underestimates of ephemeral stream presence where pumping is pervasive (fig. S8). Ephemeral streams will only become more prevalent as groundwater pumping intensifies and water tables lower further (*39–41*). Using Horton's scaling laws, we also find that our hydrography is likely missing an entire stream order, and thus our analysis represents a conservative estimate of ephemeral hydrography and the ephemeral pulse of CONUS drainage networks (see the supplementary materials for details).

The significance of the ephemeral contribution to drainage networks (Figs. 1 and 2) is underpinned by how often they flow (Fig. 3). Because ephemeral streams have no groundwater component, their flow frequency is controlled by surface runoff and interflow. This means that we can use long-term runoff patterns and an operational threshold for flow to make first-order assessments of how frequently ephemeral streams flow (see the supplementary materials and fig. S31). Here, we used 27 years of daily interpolated precipitation data (*42*) and long-term basin-averaged runoff data (*43*) to predict that ephemeral streams flow, on average across basins, 101 ± 30 days per year, but with a large fraction of basins only flowing ~0 to 10 days in an average year (Fig. 3A, inset). When ephemeral streams do flow, it is usually during late spring or early summer (fig. S32). Ephemeral flow frequency manifests as a balance of evapotranspiration, the size and frequency of precipitation events, and antecedent moisture conditions influencing runoff generation. For example, across western basins, ephemeral streams only flow 46 days a year on average, whereas across eastern basins, they flow an average of 173 days. In the arid Southwestern US, this drops to an average of 4 days a year.

Our simple model uses only interpolated precipitation data, runoff data, and an operational definition for streamflow. It reasonably matches in situ sensor data of catchment-averaged ephemeral flow frequency in the driest and wettest basins, but has reduced accuracy in basins with more moderate ephemeral flow frequencies (Fig. 3, B and C). We stress that very few data exist on ephemeral flow frequency at the drainage network scale (see the supplementary materials), and our initial modeling is purposefully simplistic. Future work should explore basin-scale ephemeral runoff generation across distributed sensor networks to refine our modeling.

## Implications for downstream water quality

Given such infrequent flow, our results suggest that ephemeral streams likely dominate drainage network responses to storm events, shunting pollutants and other solutes downstream at even greater rates than suggested here under mean annual conditions (*1*, *44*). The exact impacts of ephemeral discharge on constituent and pollutant loads is context dependent. However, the mobilization or delivery of most elements, nutrients, and pollutants scales with discharge (*45*, *46*) and is dominated by inputs from headwater streams (*17*, *18*), of which 80% of CONUS first-order stream extent is ephemeral according to our model. Thus, we would expect the importance and impacts of ephemerally sourced water on stream and river chemistry to be high in downstream regions that have accumulated large ephemeral water contributions (regardless of the specific loadings). However, this is a relatively simple interpretation of a complex process: the sourcing, transformation, and fate of pollutants, sediment, and other elements in space and time. It is important to stress that more research is needed across different biomes regarding variability in the degree and timing of connectivity of ephemeral streams at the basin scale to fully determine the impacts on water resources (*47*).

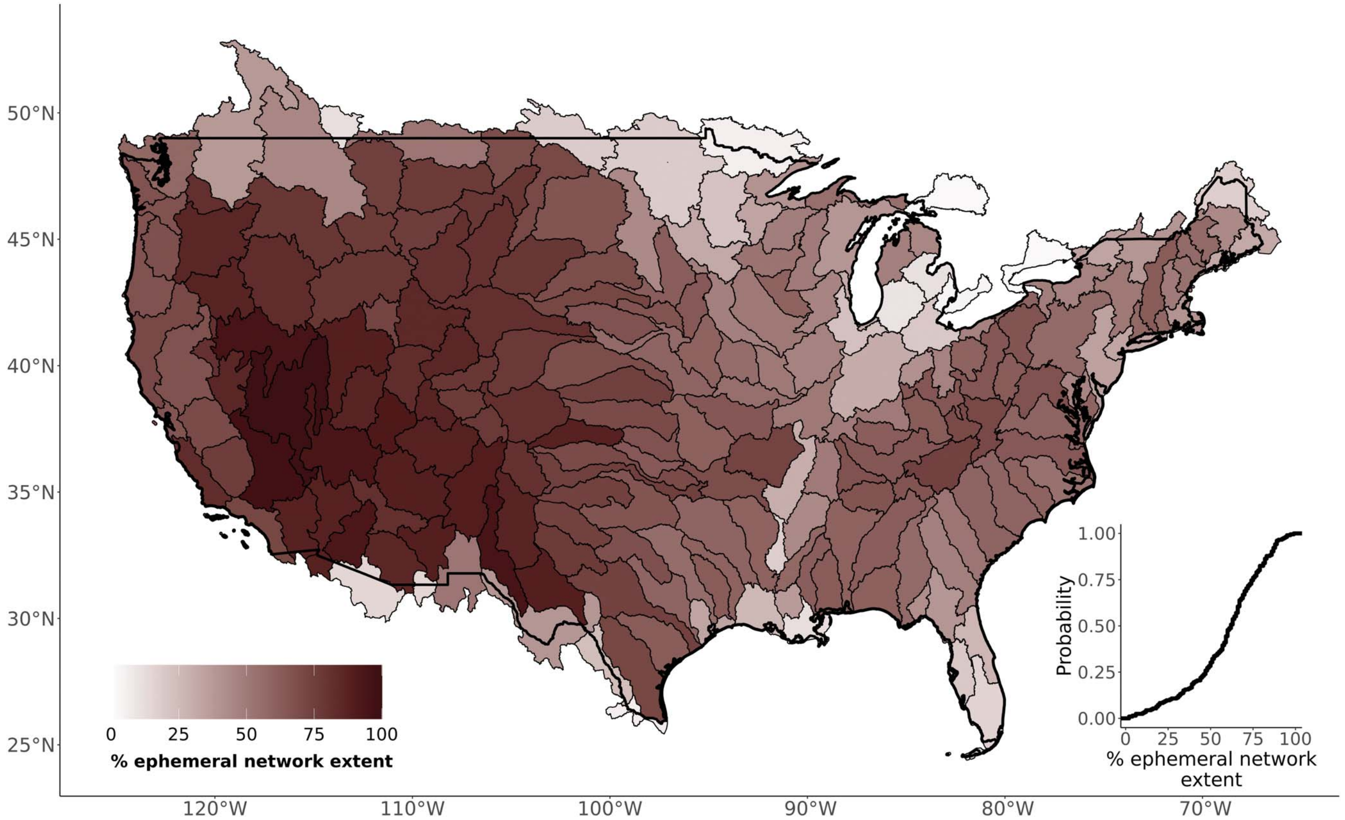

**Fig. 4. Extent of the ephemeral network.** CONUS map of the percentage of the drainage network extent that is ephemeral per our model. Inset shows the empirical cumulative distribution function of the basins.

Our findings show that ephemeral streams are a likely pathway through which pollution may influence downstream water quality, a finding that can inform evaluation of the consequences of limiting US federal jurisdiction over ephemeral streams under the CWA. In this context, we assessed the geographic extent of the CWA with and without inclusion of ephemeral streams. We found that, on average across basins, ephemeral streams account for 59% of all drainage network extent (Fig. 4). However, this is underestimated due to the previously discussed lack of groundwater pumping, a missing stream order, and a lower bound on model resolution (fig. S12 and the supplementary materials). Even as an underestimate, this still represents an upward revision of the only previous CONUS mapping effort finding that 43 to 56% of the CONUS river network extent is ephemeral but with acknowledged errors of omission (*12*).

Taking the results shown in Figs. 1 to 4 in aggregate, along with regional assessments of headwater contributions to downstream water quality (*17*, *18*) and recent global assessments of nonperennial stream extent (*8*, *12*, *14*), a consistent picture emerges. Nonperennial rivers (in particular, ephemeral streams) disproportionately influence river water composition along the entire drainage network, from small headwaters that are almost entirely nonperennial all the way to the major navigable mainstems of the HUC4 river systems in this study. This ephemeral influence directly implicates downstream water quality standards: Excluding ephemeral streams from coverage under the CWA would substantially narrow the extent of federal authority to regulate water quality in the United States.

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## SUPPLEMENTARY MATERIALS

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Materials and Methods
Supplementary Text
Figs. S1 to S32
Tables S1 to S4
References (*50*–*86*)

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