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Key Points:

- Three metrics reveal regional and human-driven patterns of nonperennial flow: no-flow fraction, day of first no flow, and dry-down duration
- Streams with human modifications generally dry more quickly than unmodified streams, especially in California and the Southern Great Plains
- Climate strongly influences no-flow fraction and timing, but physiographic variables are more important for the duration of dry down

Supporting Information:

- Supporting Information S1

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Spatial Patterns and Drivers of Nonperennial Flow Regimes in the Contiguous United States

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Abstract Over half of global rivers and streams lack perennial flow, and understanding the distribution and drivers of their flow regimes is critical for understanding their hydrologic, biogeochemical, and ecological functions. We analyzed nonperennial flow regimes using 540 U.S. Geological Survey watersheds across the contiguous United States from 1979 to 2018. Multivariate analyses revealed regional differences in no-flow fraction, date of first no flow, and duration of the dry-down period, with further divergence between natural and human-altered watersheds. Aridity was a primary driver of no-flow metrics at the continental scale, while unique combinations of climatic, physiographic and anthropogenic drivers emerged at regional scales. Dry-down duration showed stronger associations with nonclimate drivers compared to no-flow fraction and timing. Although the sparse distribution of nonperennial gages limits our understanding of such streams, the watersheds examined here suggest the important role of aridity and land cover change in modulating future stream drying.

Plain Language Summary A majority of global streams are nonperennial, flowing only part of the year, and are critical for sustaining flow downstream, providing habitat for many organisms, and regulating chemical and biological processes. Using long-term U.S. Geological Survey measurements for 540 watersheds across the contiguous United States, we mapped patterns and examined the causes of no-flow fraction, the fraction of each climate year with no flow, no-flow timing, the date of the climate year on which the first recorded no flow takes place, and length of the dry-down period, the average number of days from a local peak in daily flow to the first occurrence of no flow. We found differences in patterns of no-flow characteristics between regions, with higher no-flow fraction, earlier timing, and shorter dry-down duration in the western United States. No-flow fractions were greater and less variable in natural watersheds, while no-flow timing was earlier and dry-down duration was shorter in human-modified watersheds. Aridity had the greatest effect on intermittence across the United States, but unique combinations of climate, biophysical, and human impacts were important in different regions. The number of gages measuring streamflow in nonperennial streams is small compared to perennial streams, and increased monitoring is needed to better understand drying behavior.

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1. Introduction

Nonperennial streams constitute over half of the global stream network length (Datry et al., 2014), and almost 70% of the network in dry regions of the United States (U.S.; Goodrich et al., 2018; Turner & Richter, 2011) and Australia (Schneider et al., 2017). They support critical ecological functions and diversity (Stubbington et al., 2017), including habitat for terrestrial organisms (Dodds et al., 2004, 2019), regulation of downstream dissolved nutrients (Von Schiller et al., 2011), organic carbon availability (Hale & Godsey, 2019; Zimmer & McGlynn,), and regional diversity following alternating wet and dry phases (Bogan & Lytle, 2011; Crabot et al., 2020).

The streamflow regime—that is, the magnitude, frequency, duration, timing, and discharge variance ("flashiness")—is an essential component of the ecological template that defines riverine and riparian ecosystems (Costigan et al., 2015; Naiman et al., 2008; Poff et al., 1997). Numerous hydrologic metrics summarize hydrograph properties (e.g., Olden & Poff, 2003). Among these, "no flow" is the most commonly used in classifying nonperennial waters because it affects stream biogeochemistry (Dahm et al., 2003) and ecosystem processes during flow (Allen et al., 2019; Boulton & Lake, 2008; Jaeger et al., 2014) and drought (Davey & Kelly, 2007; Ledger et al., 2012; Ludlam & Magoulick, 2009). Although less studied, the timing and rate of stream drying are also important for policy implications, and their impacts on biogeochemical (Von Schiller et al., 2011) and biotic processes (Storey, 2016; Vadher et al., 2018). Because drying is becoming increasingly common (Allen et al., 2019; Döll & Schmied, 2012; Jaeger et al., 2014, Pekel et al., 2016; Perkin et al., 2017) and drying patterns vary in both space and time, there is a critical need to understand the patterns and causes of nonperennial flow (Vörösmarty et al., 2010).

Both natural and anthropogenic forcings can dry streams (Zimmer et al., 2020). Climate has been identified as a primary driver of nonperennial streamflow regimes at large scales (Eng et al., 2019; Kennard et al., 2010). However, the relative importance of additional factors including geology (Lovill et al., 2018), biophysical characteristics such as vegetation and topography (Dodds, 1997; Katz et al., 2012; Mayer & Naman, 2011), and human water use (Datry et al., 2014; de Graaf et al., 2019; Döll & Schmied, 2012; Larned et al., 2010) is not well understood.

We hypothesize that the wide differences in climate, vegetation, topography, and human water use across the contiguous U.S. (herein "CONUS") will result in identifiable differences in the drivers of nonperennial river flow regimes across broad ecoregions, and that these differences can be quantified using a targeted subset of available flow metrics. To test this, we (1) identified spatial patterns in no-flow regimes, specifically the no-flow fraction, timing of first no flow, and the duration of the dry-down period and (2) determined the regional importance and hierarchy of drivers of these no-flow metrics.

2. Methods

We examined daily streamflow data from 540 nonperennial U.S. Geological Survey (USGS) GAGES-II watersheds (Falcone, 2011) with at least 10 years of data from 1979 to 2018 and analyzed all available data within that time frame. This period coincides with the availability of high spatial and temporal resolution climate data. We selected gages that had an average of at least 5 and no more than 360 days of reported no flow per year, with less than 10% daily values missing per year. Of the 540 watersheds, 152 are classified as "reference" by Falcone, 2011, meaning streamflows are minimally impacted by anthropogenic activities, and 388 are nonreference. We categorized USGS gages into six regions based on U.S. Environmental Protection Agency (EPA) Level 1 ecoregions (Figure 1a).

For each gage and year, we quantified three metrics characterizing no-flow regimes over the climate year (1 April to 31 March). We specifically chose the climate year because it best bracketed the occurrence of no flow while minimizing the number of stations across the domain where zero flow occurs on the start of the year. The metrics are as follows:

1. *No-flow fraction*: number of days measuring no streamflow per climate year divided by the number of days with data for that climate year
2. *First no flow:* day of the climate year on which the first recorded no-flow observation takes place

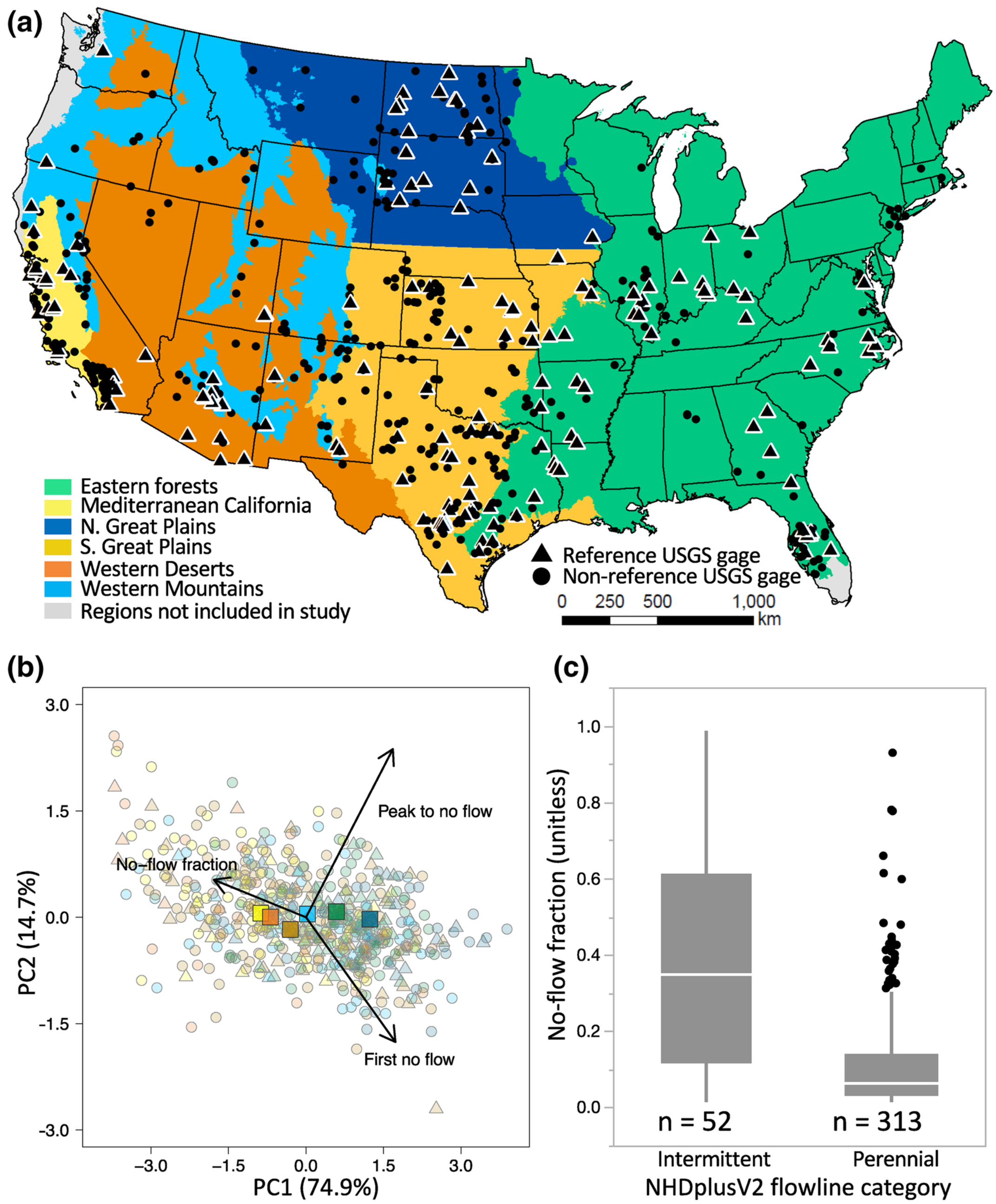

Figure 1. (a) Nonperennial streams measured by USGS reference, nonreference gages from GAGES-II plotted on EPA Level 1 ecoregions. (b) Principal component analysis of no-flow metrics for all gages. Gages are ordinated in multivariate space based on three mean annual metrics, shown as arrows that capture proportional loadings of each metric. Small symbols represent individual gages while large symbols represent centroids for all gages within each ecoregion. (c) Boxplot comparison of no-flow fraction categorized by the National Hydrography Dataset (NHD) gage-reach flow classification. One hundred and seventy-five gage reaches used in this study did not have flow classifications in NHDplusV2 (USGS, 2019). EPA, Environmental Protection Agency; USGS, U.S. Geological Survey.

3. *Peak to no flow:* average number of days from a local peak in daily flow to the first occurrence of no flow, herein referred to as the dry-down duration. Only local peaks greater than the 25th percentile of long-term mean daily flow at each site are considered, and daily flows were rounded to the nearest 0.1 of a cubic foot per second to avoid uncertainty in zero flow (Zimmer et al., 2020)

These three metrics describe key aspects of the no-flow regime that influence a stream's hydroecological patterns and processes. Although first no flow is inversely correlated with no-flow fraction (Figure 1b, $r = -0.70$), we include both metrics because they have different ecological and management implications. Annual no-flow metrics are calculated for the climate year (1 April to 31 March) to reduce the likelihood of no-flow events spanning multiple years (following Dudley et al., 2019; Feaster & Lee, 2017; Smakhtin, 2001). We used principal component analysis to summarize and visualize relationships between our three focal metrics across all gages.

To evaluate potential drivers of no-flow metrics we extracted climatic, physiographic, land cover, and human alteration characteristics for each watershed. Climate variables included daily precipitation (P), mean air temperature (Tmean), potential evapotranspiration (PET), Palmer Drought Severity Index (Abatzoglou, 2013), and snow water equivalent (SWE; Broxton et al., 2019). These were aggregated to climate year values for 1979–2018; we used the mean annual value for each climate variable in all subsequent analyses. We also extracted mean annual precipitation seasonality for water years 1980–2010 (Falcone, 2011). Physiographic characteristics included drainage area and watershed mean values of elevation, slope, permeability, soil available water capacity, topographic wetness index, depth to bedrock, porosity, and total subsurface storage (Falcone, 2011; Gleeson et al., 2014; Hengl et al., 2017). Land cover and human alteration characteristics included percent cover for forested, developed, cultivated, and impervious classes for the year 2006 (Xian & Homer, 2010) and average annual freshwater withdrawals for the year 2005 (Falcone, 2011). Dam storage is the total volumetric storage of all dams within the watershed from the National Inventory of Dams in 2010 (US Army Corps of Engineers, 2010).

We developed random forest models relating watershed characteristics to each no-flow metric (Addor et al., 2018; Konapala & Mishra, 2020) to quantify the drivers of spatial variability in no-flow metrics. Random forest models identify the relative importance of explanatory variables and have multiple benefits over traditional multivariate methods (see Addor et al., 2018). We constructed a total of 42 random forest models, based on a combination of no-flow metrics ($n = 3$), spatial domains ($n = 7$; six regions + national), and gage type ($n = 2$; reference gages or all gages; see Supplemental Information). We ranked variables by mean square error increases if they were removed (incMSE%) to identify primary drivers of no-flow metrics and the relative importance of climate and watershed properties in controlling no flow. Further detail on all analyses is included in Text S1.

3. Results and Discussion

3.1. Three Metrics Reveal Spatial Patterns in Mean Annual No Flow and No-Flow Variability

In this study, we calculated a suite of no-flow metrics (Tables S7 and S8) and identified no-flow fraction, date of first no flow, and peak to zero flow as critical metrics due to their predominance in ecological assessments as well as the hydrograph characteristics they represent. The three no-flow metrics were moderately to strongly correlated (|0.38–0.74|), with longer no-flow fraction corresponding to earlier and faster drying. Using these no-flow metrics, the first two principal components explained 89.6% of the variability in the data set (Figure 1b); notably, peak-to-zero flow is nearly orthogonal to no-flow fraction and first no flow, revealing that this metric contains different information and may reflect different drivers of nonperennial flow.

Mean no-flow fractions were generally lower and the first day of no flow was typically later in wetter areas of the U.S. (Figures 2a and 2b and Table S1). The dry-down duration had less pronounced spatial patterns, suggesting that nonclimatic drivers may control this metric (Figure 2c). Areas of the U.S. with lower no-flow fractions had greater year-to-year variability as revealed by the coefficient of variation (Figures 2d and Figure S4). Regions with later first date of no flow tended to have lower year-to-year variability (Figure 2e). Variability in peak-to-no-flow duration was greatest in drier portions of the U.S. and lowest in wetter portions of the U.S. and showed less intraregional variability than the other two no-flow metrics (Figure 2f). Finally, existing flow categories from NHDPlusV2 (USGS, 2019) compared poorly to observed no-flow fractions (Figure 1c), suggesting the current national best guess of flow condition is inaccurate as evidenced in prior studies (Fritz et al., 2013; Jaeger et al., 2019) and underscoring the need for improved nonperennial stream mapping (e.g., Walsh & Ward, 2019) and additional gaging.

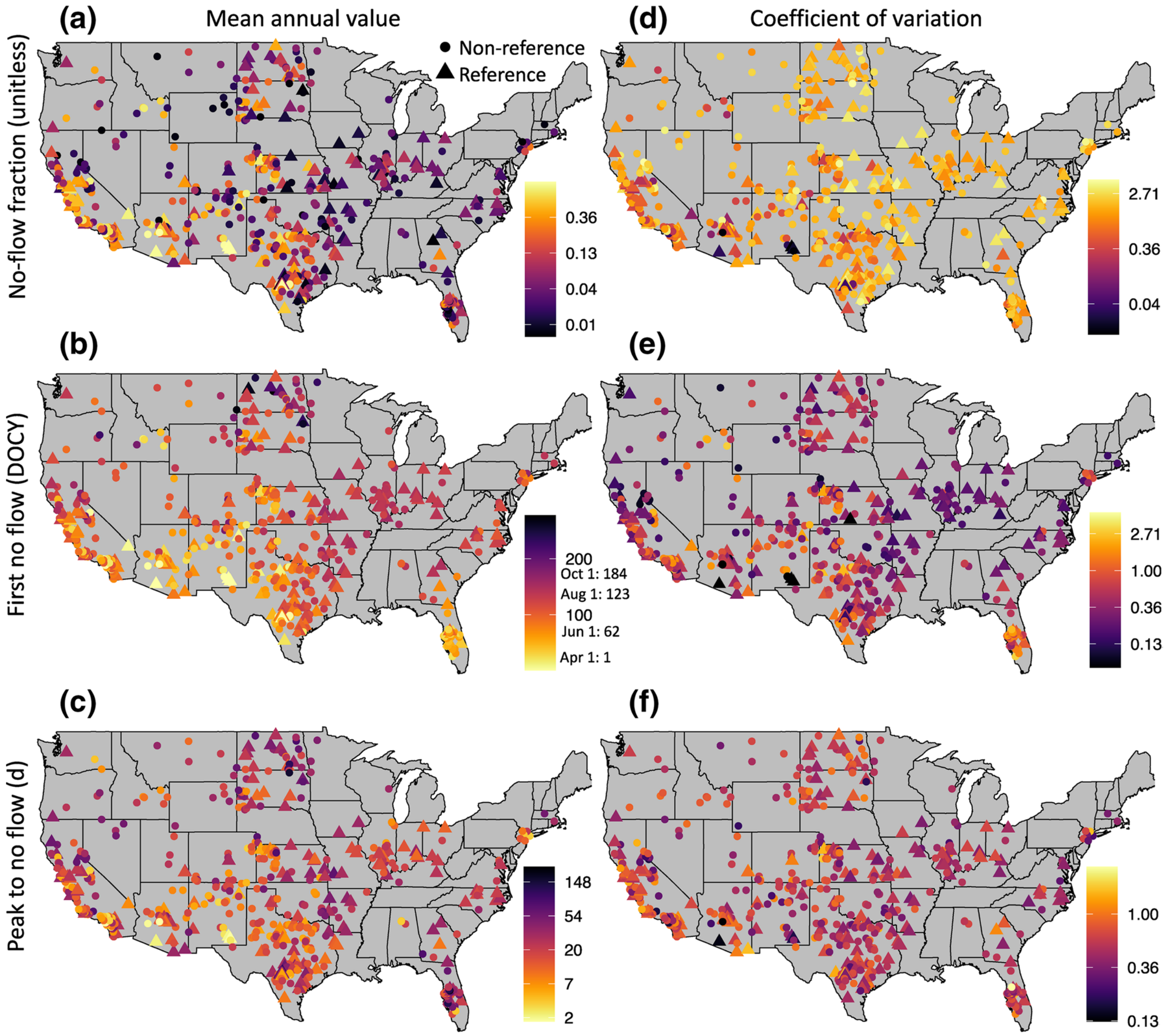

Figure 2. Spatial distribution of mean annual no-flow metrics (a–c) and their coefficients of variation (d–f).

3.2. Differences Emerge From Regional and Human-Modification Separations

Ecoregions exhibited different ranges of values for each metric (Figure 3), highlighting regional variability in characteristics of nonperennial flow. This variability suggests that Federal policy (e.g., Waters of the United States [WOTUS] and Clean Water Act [CWA]) has to account for regional variability in no-flow characteristics for effective implementation at the local scale. For example, gaged streams in Mediterranean California have higher no-flow fraction and dry earlier and more rapidly than those in the Northern Great Plains (Table S4), so more streams in California may be affected by policies related to nonperennial flows.

Patterns of no-flow metrics were similar among reference and nonreference gages, however, there were several key exceptions. Across CONUS, the date of first no flow was 16 days earlier, on average, at nonreference gages than reference gages (mid-July vs. early-August; Figure 3 and Table S1). This pattern did not hold for all regions, particularly in the Western Desert where reference gages dry in the early spring while nonreference streams retain water into August, likely reflecting irrigation water through the growing season. Streams dry down significantly slower in nonreference watersheds across CONUS, and particularly in Mediterranean California and the Southern Great Plains (Figure 3). Impervious cover was higher in nonreference gages for these regions (Table S1), consistent with previous research that has observed flashier runoff in human-impacted watersheds (Kaushal & Belt, 2012), although these impacts vary regionally (McPhillips

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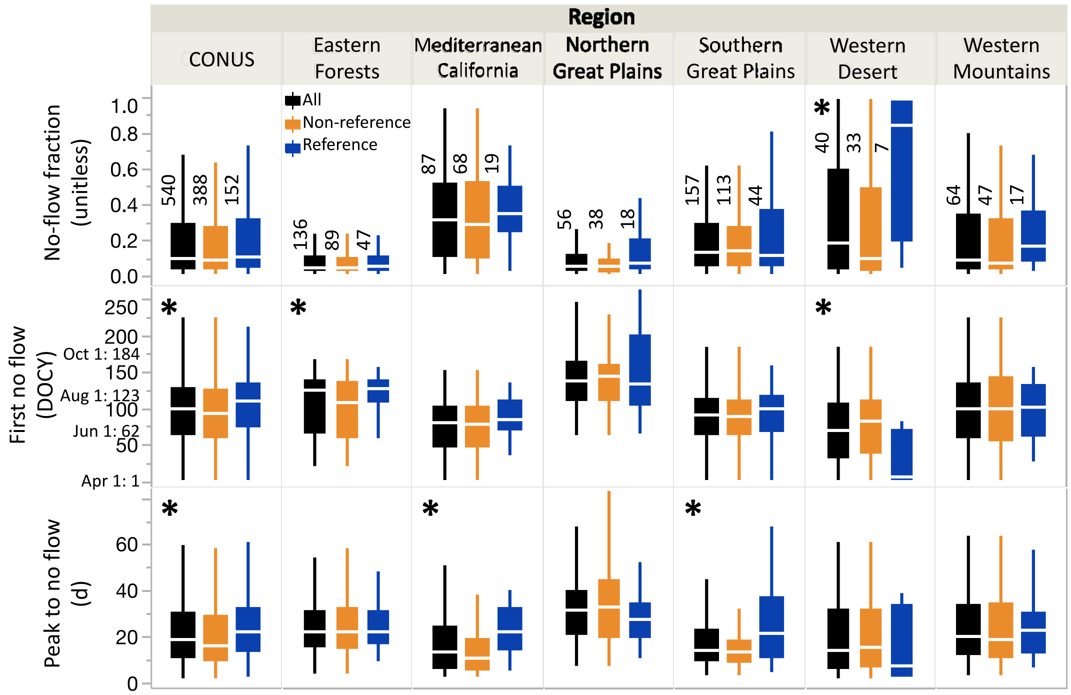

Figure 3. Boxplots of no-flow metrics for each ecoregion and sample category: all, nonreference, reference. Vertical numbers adjacent to boxplots report the number of watersheds in each grouping. Asterisk in the upper left of a panel indicates a significant difference between reference and nonreference groupings using Wilcoxon Rank Sum test (*p*-value < 0.05). For pairwise significant differences between ecoregions, see Table S4. First no flow is based on the day of climate year (DOCY): day 1 is April 1, 184 is October 1.

et al., 2019). Human-derived impacts that we observed varied with region and metric and highlight the need for more in-depth understanding of how human modifications impact drying processes. In the next section, we explore how widespread human alterations to the hydrologic cycle couple with other factors to drive no-flow characteristics.

3.3. Climate Drives CONUS No-Flow Fraction and Timing While Physiographic Variables Drive Dry-Down Duration and Regional No-Flow Variability

Across CONUS, climate was a dominant driver of no-flow regimes at reference (Figure 4) and all gages (Figure 5). The annual ratio of precipitation to potential evapotranspiration (P/PET; herein “aridity”) was the strongest predictor of all no-flow metrics for reference gages in random forest models (Table S5). For CONUS, climate explained more variability in no-flow fraction and date of first no flow than in peak-to-no-flow duration (Figure 5), and within ecoregions, aridity was the dominant driver of no-flow fraction in the Southern Great Plains and Western Deserts (Figure 5 and Table S5). Other climate variables were important in other ecoregions: mean annual air temperature was the dominant driver in Mediterranean California and Western Mountains where higher temperatures correspond to higher no-flow fractions, and snow fraction (SWE/P) in Eastern Forests where higher snow fractions correspond to lower no-flow fractions. Given that climate explains most of the variability in no-flow metrics, continued intensification of the hydrologic cycle may substantially alter regional characteristics of nonperennial systems (Huntington, 2006).

Although climate seems to be the primary driver of no-flow fraction and timing at CONUS scale, nonclimate variables explained a greater fraction of variability for peak-to-no-flow duration in all watersheds, including reference watersheds with minimal human influence (Figure 5). This is consistent with the absence of clear regional patterns in peak-to-no-flow duration (Figure 2). Regionally, permeability, depth to bedrock, mean watershed slope, and drainage area were the most important explanatory variables for peak to no flow (Table S5). Streamflow dry down involves complex processes (Costigan et al., 2017; Stoelzle et al., 2013), and watershed structure and subsurface characteristics likely regulate these components of the no-flow

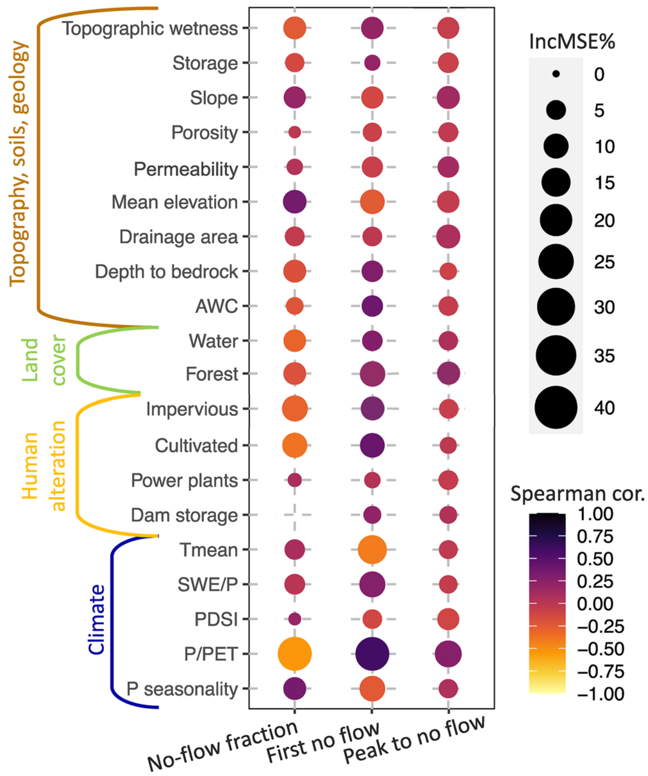

Figure 4. Explanatory variables in random forest models for no-flow metrics in CONUS reference watersheds colored by Spearman rank correlations and sized by percentage increase in mean standard error (incMSE%) of the model if the explanatory variable is removed. AWC, soil available water capacity; CONUS, contiguous United States; PDSI, Palmer Drought Severity Index; P/PET, precipitation/potential evapotranspiration; P seasonality, precipitation seasonality; SWE/P, snow water equivalent/precipitation.

regime, as previously shown for perennial streams (Addor et al., 2018; Tashie et al., 2020). Rapid drying may indicate the prevalence of surface and shallow subsurface flow paths while slower drying may imply greater groundwater connection.

Human impacts emerged as important drivers of no-flow fraction and peak-to-no-flow duration in some regions in addition to physiography (Figure 5). Impervious area was the most common human driver of no flow (Table S5) and was significantly ($p < 0.05$) negatively correlated with peak-to-no-flow duration for CONUS as well as for the Eastern Forests and Mediterranean California ecoregions. Since peak-to-no-flow duration decreases with increasing impervious area, human-altered watersheds may generally dry more rapidly than their natural counterparts leading streams to be dry for longer, though recent studies highlight opposing effects of impervious area on low flows (Bhaskar et al., 2020; Ledford et al., 2020).

Dam storage was a driver of no-flow fraction, first no flow, and peak-to-no-flow duration in Northern Great Plains reference watersheds, but correlations were weak and insignificant ($p > 0.1$). These watersheds are classified as reference because they are the least impacted in the region, yet still contain small dams, reflecting the extent of human modification on the plains (Figure S3, Table S5). While we did not find dam storage to be a major driver of nonperennial flow, most dams have minimum low-flow requirements, thereby excluding downstream gages from our analysis by extending the streamflow season (Carlisle et al., 2019).

Natural and anthropogenic drivers of no-flow metrics differ across scales (Costigan et al., 2015; Snelder et al., 2013), and our analysis may not capture local effects. For example, local water table fluctuations and shifts in streambed hydraulic conductivity act at smaller scales than captured by our analysis (Konrad, 2006; Larned et al., 2010; Morin et al., 2009; Sharma & Murthy, 1994). Similarly, anthropogenic drivers including groundwater abstraction, small-scale surface water withdrawals or diversions may not be captured at watershed scales (Zimmer et al., 2020). Ultimately, interactions between local processes, regional drivers, and climate determine where and when nonperennial flow occurs (Snelder et al., 2013).

4. Implications, Limitations, and Conclusions

The three metrics used in this study characterize important components of the hydrologic regime of nonperennial systems, reflect different aspects of flow variability that are important for stream organisms, and elucidate regional and human-driven patterns. Though climate is the primary driver of no-flow fraction and timing, we find that physiographic variables control the variability in dry-down durations. Additionally, we show that the dry-down duration correlates weakly with no-flow fraction and first no-flow timing, suggesting dry-down duration represents distinct hydrologic processes. Overall, we found that no-flow fraction was similar between reference and human-altered watersheds, while human impacts led to significantly earlier and more variable first no-flow dates and shorter dry-down durations, especially in Mediterranean California and the Southern Great Plains.

Several factors limit the scope of inference of our study. First, nonreference watersheds were characterized by larger drainage area, water storage capacity, and permeability than reference watersheds. Nonreference watersheds were also drier and warmer, with more seasonal precipitation, potentially promoting lower flows during drier seasons (Costigan et al., 2017; Dettinger & Diaz, 2000). The sample size for reference watersheds is considerably smaller than nonreference across all ecoregions, and without a better understanding

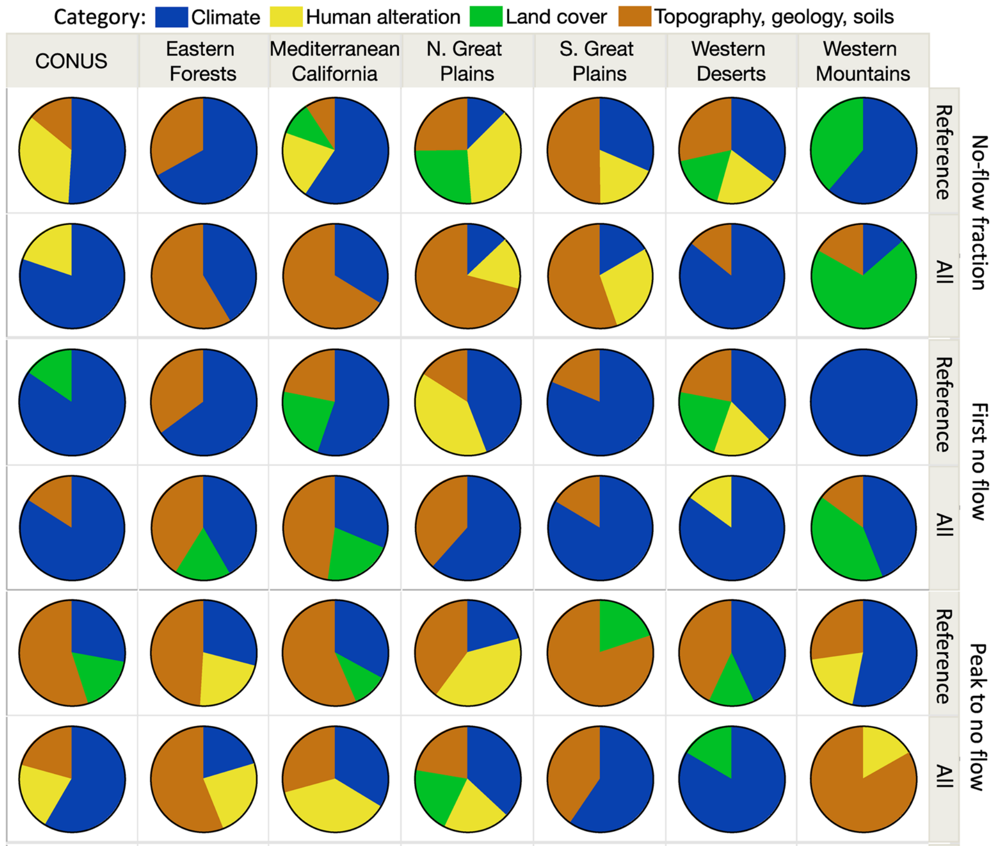

Figure 5. Variable category for the top five predictors in each model for combinations of no-flow variable and sample. Pie slice size corresponds to the fraction of incMSE% contribution for each category: climate; human alteration; land cover; topography, soils, and geology. For information on the top five variable hierarchy and incMSE% for each model, see Table S5.

of how nonperennial stream regimes function in reference watersheds, it remains challenging to decipher the impacts of human modifications on these systems. Nested measurements within drainage networks could reveal where streams are gaining or losing flow, and the impacts of local geology and topography (Kampf et al., 2020; Lovill et al., 2018; Shanafield et al., 2020; Whiting & Godsey, 2016) to clarify these processes. Additionally, our work suggests that comprehensive databases of small-scale water infrastructure would improve our abilities to predict anthropogenic effects on flow regimes beyond the current reference/nonreference designation.

These limitations highlight an immediate and fundamental need to preserve and extend availability of reference gage data, particularly in nonperennial rivers, and clarify which ecoregions need additional data. While the USGS gage network is extensive (Kiang et al., 2013), gage placement is often optimized for flood control and water supply, and gaging in nonperennial systems is often sparse (Zimmer et al., 2020). Thus, large-scale studies of streamflow variability have predominantly focused on perennial streams (e.g., Brunner et al., 2020; Vignesh et al., 2015), and less research has incorporated nonperennial streams (Kennard et al., 2010; Poff, 1996). Therefore, our ability to address changes or alterations to nonperennial stream protections may be data limited (e.g., Walsh & Ward, 2019), although we still show that changes in the hydrologic cycle could drive drying patterns.

Future efforts could examine long-term no-flow trends driven by combined climatic and anthropogenic changes or analyze subannual patterns to discern differences in drying regimes, both of which have critical implications for aquatic ecosystems. While cross-disciplinary research on nonperennial streams is burgeoning globally (Busch et al., 2020), additional empirical research is needed to understand flow activation and dry-down mechanisms. The significant spatiotemporal variability we observe in no-flow metrics within and across ecoregions points to the need to advance understanding of spatiotemporal drivers to better manage these ecosystems. With potential increases in no-flow duration and frequency, improved understanding of drying and associated ecosystem functions will enable more robust management and regulation of nonperennial waters.

Data Availability Statement

Data sets for this research are available in the USGS ScienceBase repository at https://doi.org/10.5066/P9D-8VDHI (Hammond, 2020).

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