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High resolution spatiotemporal patterns of flow at the landscape scale in montane non-perennial streams

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Abstract
Intermittent and ephemeral streams in dryland environments support diverse assemblages of aquatic and terrestrial life. Understanding when and where water flows provide insights into the availability of water, its response to external controlling factors, and potential sensitivity to climate change and a host of human activities. Knowledge regarding the timing of drying/wetting cycles can also be useful to map critical habitats for species and ecosystems that rely on these temporary water sources. However, identifying the locations and monitoring the timing of streamflow and channel sediment moisture remains a challenging endeavor. In this paper, we analyzed daily conductivity from 37 sensors distributed along 10 streams across an arid mountain front in Arizona (United States) to assess spatiotemporal patterns in flow permanence, defined as the timing and extent of water in streams. Conductivity sensors provide information on surface flow and sediment moisture, supporting a stream classification based on seasonal flow dynamics. Our results provide insight into flow responses to seasonal rainfall, highlighting stream reaches very reactive to rainfall versus those demonstrating more stable streamflow. The strength of stream responses to precipitation are explored in the context of surficial geology. In summary, conductivity data can be used to map potential stream habitat for water-dependent species in both space and time, while also providing the basis upon which sensitivity to ongoing climate change can be evaluated.

KEYWORDS
desert, drought, flow refuge, habitat connectivity, hydrology, North American Monsoon, Sky Islands, Southwest USA

1 | INTRODUCTION

Intermittent and ephemeral streams are widely distributed across the globe and are particularly prevalent in drylands where there is strong coupling between climate, streamflow, and shallow groundwater over multiple timescales (Chen, Michaelides, Grieve, & Singer, 2019; Messager et al., 2021; Quichimbo, Singer, & Cuthbert, 2020). These streams often are the main source of moisture in otherwise dry landscapes, making them important hotspots of biodiversity (Bogan, Boersma, & Lytle, 2015; Datry, Larned, & Tockner, 2014; Larned, Datry, Arscott, & Tockner, 2010). As such, understanding the timing and controls of flow in ephemeral and intermittent streams is needed to map potential habitats in drylands, and assess how the distribution of these habitats might shift with climate change (Hammond et al., 2021; Zipper et al., 2021). In this paper, we leverage a conductivity dataset from a network of sensors deployed in streams along an arid mountain front to investigate the spatio-temporal distribution of flow, map flow condition, identify potential controls on surface flow and sediment moisture, and establish a seasonal classification of flow for dryland streams. The resulting spatial and temporal maps of temporary flow can provide useful information for assessment of habitat suitability for a wide range of species, and to support improved interpretations of the linkages between climate forcing and mountain front hydrology.

Dryland regions, defined as areas where plant productivity is limited by water availability, cover about 41% of the land surface (Millennium Ecosystem Assessment, 2005) and are dominated by temporary streams that dry at least once per year (Messager et al., 2021). Significant drylands include the southwestern region of the United States, where ~81% of streams are classified as non-perennial, a proportion which rises to 94% in Arizona (Levick et al., 2008; Nadeau & Rains, 2007). Non-perennial streams occasionally dry out (fully dry streambed), and can be classified as ephemeral or intermittent, with ephemeral reaches reaching surface flow only in response to rainfall, while intermittent reaches display cycles of drying and wetting (Busch et al., 2020; Gallo, Meixner, Lohse, & Nicholas, 2020; Levick et al., 2008; Levick et al., 2015). Perennial streams flow year-round, supplied by groundwater discharge to the stream bed. Streams that alternate between perennial, ephemeral and intermittent reaches are considered interrupted or spatially intermittent (Levick et al., 2008). Streamflow permanence is controlled by various environmental factors such as rainfall distribution, evaporative demand, topography, underlying geology, streambed composition, channel morphology and vegetation (Costigan, Jaeger, Goss, Fritz, & Goebel, 2016; Goodrich, Kepner, Levick, & Wigington Jr., 2018; Levick et al., 2018; Shanafield, Bourke, Zimmer, & Costigan, 2021; Singer & Michaelides, 2014), but climate-induced aridity (balance between rainfall and evapotranspiration) is considered an overarching key driver (Hammond et al., 2021; Sauquet et al., 2021). In areas with a seasonal distribution of precipitation, such as the region of the Southwest USA affected by the North American Monsoon, flow permanence can follow this highly uneven temporal distribution (Eng et al., 2016; Singer & Michaelides, 2017).

High variability in upstream-downstream arrangement of perennial and non-perennial streams support a mosaic of habitats for plant and animal life (Boulton, Rolls, Jaeger, & Datry, 2017; Datry et al., 2014; Larned et al., 2010). Spatial and temporal variations in habitat patch distribution and composition lead to high watershed-scale species diversity (Burnett et al., 1998; Larned et al., 2010; Stromberg et al., 2015). In drylands specifically, the presence of these wet reaches contributes to the strong contrast in water availability between riparian areas and the surrounding arid landscape (Levick et al., 2015; Stromberg et al., 2015), leading to contrasts in flora and fauna both in terms of species composition and density (Goodrich et al., 2018; Levick et al., 2008; Sabathier, Singer, Stella, Roberts, & Caylor, 2021). The denser vegetation of riparian forests and wetlands is used for foraging, nesting or as migration corridors and stopovers, cool and humid refuges, and seed dispersal corridors (Datry et al., 2014; Levick et al., 2008).

More frequent and severe droughts linked to climate change are projected to significantly alter flow intermittence patterns and hydrologic connectivity in dryland streams by increasing the number of zero-flow days and the length and frequency of dry channel reaches (Jaeger, Olden, & Pelland, 2014; Sauquet et al., 2021; Zipper et al., 2021). In the United States, a general decline in surface-water availability and soil moisture is expected across the southwestern region (Seager et al., 2013), which would dramatically impact ephemeral and intermittent channels. This water-availability decline, added to other stressors such as water pumping and other flow diversions, lead to loss of wetlands and the species they host (Hendrickson & Minckley, 1985). Knowing precisely where and when there is surface flow is essential to map the distribution of potential streamside habitats, but also to anticipate habitat distribution shifts induced by climate change (Allen et al., 2019; Jaeger et al., 2014; Sauquet et al., 2021).

To understand how flow permanence varies along streams across a mountain front within a dry climatic region, we use electrical conductivity sensors to detect dryness and wetness of the streambed (Blasch, Ferré, Christensen, & Hoffmann, 2002; Chapin, Todd, & Zeigler, 2014; Jaeger & Olden, 2012). These sensors can be used in ephemeral headwaters to map perennial and intermittent flow (Adams, Monroe, Springer, Blasch, & Bills, 2006; Assendelft & van Meerveld, 2019). The fine spatial resolution and high temporal frequency of observations are capable of capturing flow variability (Arismendi et al., 2017, Larned et al., 2011) to support classification of ephemeral and intermittent streams and better understand the environmental factors governing water distribution (Jensen, McGuire, McLaughlin, & Scott, 2019). A similar method was used by Gallo et al. (2020) across the same mountain front with a limited number of sensors across three canyons, and focusing on rainfall and sediment hydraulic conductivity. We use daily conductivity from 37 sensors across 10 canyons to compare seasonal flow timing to precipitation and underlying geology. This high spatial and temporal resolution dataset, which provides daily information for all the main headwater streams on the north-eastern slopes of the mountain range, allows for an understanding of landscape-level flow patterns and helps decipher regional (rainfall) and local (geology) environmental controls on flow permanence.

2 | METHODS

We investigated spatial and temporal variability of flow by mapping daily electrical conductivity (EC) values across our study site and compared these values to daily rainfall. We then sorted each sensor in a seasonal classification to link flow condition to seasonal rainfall. This response is evaluated further by comparing rainfall and EC values over several years of variable precipitation distribution. Lastly, we compared stream reaches and their seasonal classes to permeability of the underlying geology to examine the role of geology as a potential factor to flow patterns in non-perennial streams.

2.1 | Study site

Our study site spans 10 non-perennial streams spread across the eastern side of the Huachuca Mountains, a mountain range in southeastern Arizona that is part of the Madrean Sky Islands (Figure 1a,b). The Madrean Sky Islands are scattered mountain ranges covered by oak-pine forests surrounded by low and flat valleys of semi-arid grasslands and desert scrub (Levick et al., 2018; López-Hoffman & Quijada-Mascareñas, 2012). The stream network consists of a series of intermittent and ephemeral reaches connecting scattered perennial reaches. The streams of interest are named for their canyons of drainage: Ramsey (R), Brown (B), Tinker (T), Garden (G), Woodcutters (W), Rock Spring (RS), Huachuca (H), Split Rock (SPR), Slaughter House (SL) and Blacktail (BT).

Streamflow is fed by rainfall and to a lesser extent by snowmelt and the local water table. Short but strong monsoon storms that occur from July to September comprise ~60% of annual rainfall, with less intensive winter precipitation providing the remainder. The driest season occurs before the monsoon, from May to June. Precipitation is greater at higher elevations (Figure 1c). The monsoon brings intense thunderstorms that turn into runoff and floods, while milder winter rains and snowmelt more readily infiltrate and provide soil moisture (Loik, Breshears, Lauenroth, & Belnap, 2004; Vera et al., 2006).

The streams of the Huachuca Mountains cross over a diversity of geologic units (mudstone, limestone, quartzite, and granite), as well as several faults (Brown, Davidson, Kister, & Thomsen, 1966) before reaching the lowlands. Channels have cascade and step pool morphology at the upper extents typical of steep headwater streams and transition to pool riffle morphology in the downstream valley (Wohl & Pearthree, 1991). The valley surrounding the mountains is composed of permeable basin fill, terrace deposits and stream alluvium. Water crosses the valley underground within the basin fill (or in washes during the strongest monsoon events) to reach the two main intermittent rivers draining the area: the San Pedro River to the east, and the

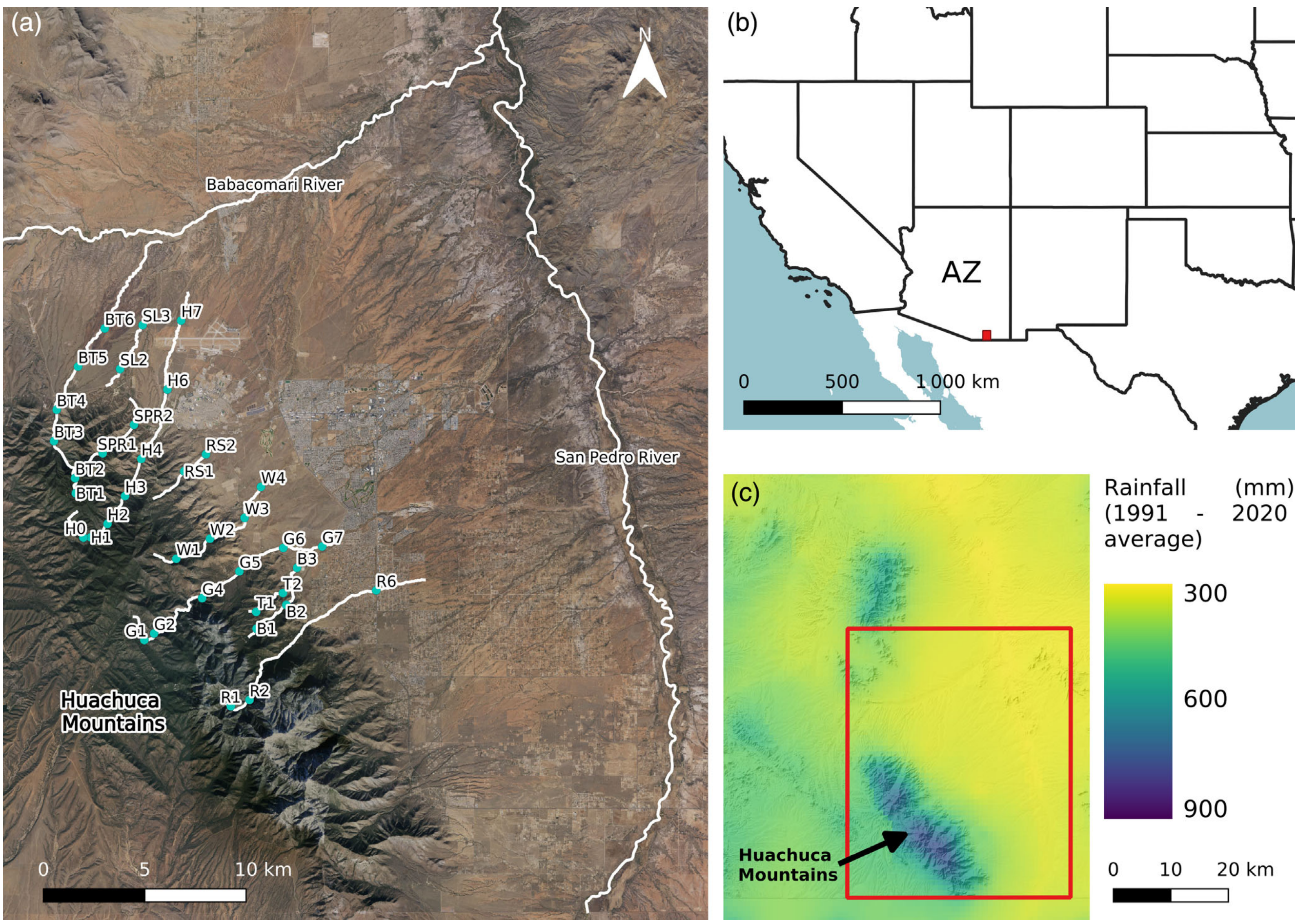

FIGURE 1 Study area (National Agriculture Imagery Program image) with streams and location of sensors (BT, Blacktail; SL, Slaughter House; SPR, Split Rock; H, Huachuca; RS, Rock Spring; W, Woodcutters; G, Garden; T, Tinker; B, Brown; R, Ramsey Canyons) (a), location of the study site in Arizona, United States (b) and regional annual rainfall distribution (from PRISM, https://prism.oregonstate.edu/normals/) (c). White lines represent the main rivers and the mountain streams equipped with sensors [Color figure can be viewed at wileyonlinelibrary.com]

Babocomari River to the north (Gungle, 2006; Levick et al., 2008) (Figure 1a).

2.2 | Sensor array

A total of 37 electrical conductivity (EC) sensors were installed along 10 streams of the Huachuca Mountains, and operated between 2010 and 2014 (Sabathier & Jaeger, 2022) (Figure 1a). Originally, 44 sensors were installed, but seven were omitted from this study because of short recording periods or quality issues. These sensors were initially installed to quantify flow condition (flow, wet or dry) through both time and space, including longitudinal flow connectivity (Jaeger & Olden, 2012). Their high spatial and temporal resolution is useful for capturing responses to local and short-term climatic events over wide areas (Adams et al., 2006; Assendelft & van Meerveld, 2019; Jensen et al., 2019). These EC sensors recorded relative conductivity every 15 minutes, with large values reflecting surface water presence, and smaller values reflecting dry channel conditions. Conductivity values are considered relative to each other consistent with other studies (Jensen et al., 2019; Warix, Godsey, Lohse, & Hale, 2021) as sensor values were not calibrated with a solution of known conductivity. The data collected can be used to detect onset and end of flow in non-perennial streams that are too small or too dry to be equipped with streamflow gauges (Blasch et al., 2002; Chapin et al., 2014; Goulsbra, Lindsay, & Evans, 2009; Stromberg et al., 2015).

We used daily average values of relative conductivity from the June 1, 2010 to May 31, 2011 to analyze flow permanence. This time frame was chosen because it covers a full year during which all 37 sensors operated without gaps. To investigate inter-annual variability of flow, we used four sensors (G2, H7, T1 and T2) that recorded EC for 3 years. Electrical conductivity records a low and constant value in dry sediment and progressively increases in wet sediments, finally exhibiting an abrupt increase at the onset of streamflow (Blasch et al., 2002; Goulsbra et al., 2009). Because the sensors are buried to a depth of <10 cm in the channel bed, sediment type or grain size distribution can affect the recorded values (Blasch et al., 2002), and may also cause a delay between the onset or cessation of flow and observed electrical conductivity (Adams et al., 2006; Blasch et al., 2002).

Sensors G4 (Garden Canyon) and H3 (Huachuca Canyon) were located close to U.S. Geological Survey (USGS) stream gauges 9470800 and 9471310, respectively. Daily streamflow data were downloaded from the USGS database (U.S. Geological Survey, 2022). The co-location of conductivity and flow data allowed us to directly classify conductivity in terms of flow permanence. We compared gauged stream discharge with adjacent EC sensor values for the same time-step and period (Adams et al., 2006; Blasch et al., 2002; Stromberg et al., 2015) (Figure 2a,b). Some discrepancies between these datasets are expected, due to mismatches in precise location and measurement resolution, but their comparison provides an indication of how EC sensors react to flow conditions.

Acknowledging the uncertainty of this method and the potential influence of spatial variability in stream bed substrate, we focus on general categories covering a range of values. Thus, we built a scale between relative conductivity values and flow state (dry, wet sediment and flow) (Table 1). A relative conductivity value of −90 is considered to represent dry sediment, as it is the lowest values reached by the sensors, and it is the only value that remains constant with no variations for days or weeks at a time. The threshold for water in the stream is 0 as this is the value reached during the sharpest conductivity peaks, following the strongest rainfall events (Figure 2).

2.3 | Flow condition classification

Relative conductivity was further classified into two classes: dry and wet, with the wet class including wet sediment and flow (or standing water) (Table 1). The seasonal classification of each sensor was established using data from the June 1, 2010 to May 31, 2011. In July 2011, an apparent battery issue caused values for all sensors to drop ("dry sediment" baseline dropped from −97 to −138). An offset was applied for all values recorded after July 24, 2011 to bring the values back in line to pre-July 2011 levels (see supplementary figure S1) and used for the analysis of inter-annual variability.

Flow condition was reported as continuous (and represented by a continuous color ramp, Table 1), with no hard limits between flow, wet sediment and dry streambed classes in order to accommodate the potential uncertainties in EC values as a metric of flow. In maps displaying daily flow condition across sensors throughout the stream network, inverse distance weighting (IDW) interpolation in the longitudinal direction was used to reconstruct a continuous flow condition record at all points along the channel of each stream. While we do not know precisely how flow condition changes between sensors, the IDW interpolation provides a visualization tool to represent the dynamics of flow connectivity along each stream.

To understand the impact of rainfall on flow permanence, we used daily rainfall from PRISM (https://prism.oregonstate.edu/recent/), a gridded dataset at 4-km resolution, modeled by interpolation from ground stations, climate data and elevation (Daly et al., 2008). Rainfall from June 2010 to May 2011 was only 351 mm, which is a characteristically dry year compared to the 30-years (1991–2020) average precipitation from PRISM of 409 mm. Rainfall distribution across the year was also slightly unusual, with a stronger monsoon in 2010–2011 (308 mm vs. 235 mm for the 30-year average), but a drier winter and spring.

We defined a classification based on temporal distribution of flow condition throughout the year, a common way to classify ephemeral streams (Costigan et al., 2016; Eng et al., 2016; Sauquet et al., 2021). Daily rainfall was used to define the seasons based on precipitation distribution. We divided the year into four seasons, based on rainfall temporal distribution: dry spring (May–June), the summer monsoon (July–September), dry autumn (October–November) and wet winter (December–April). For each sensor, we counted the number of "wet" days (wet sediment or flow, relative conductivity above −90, table 1)

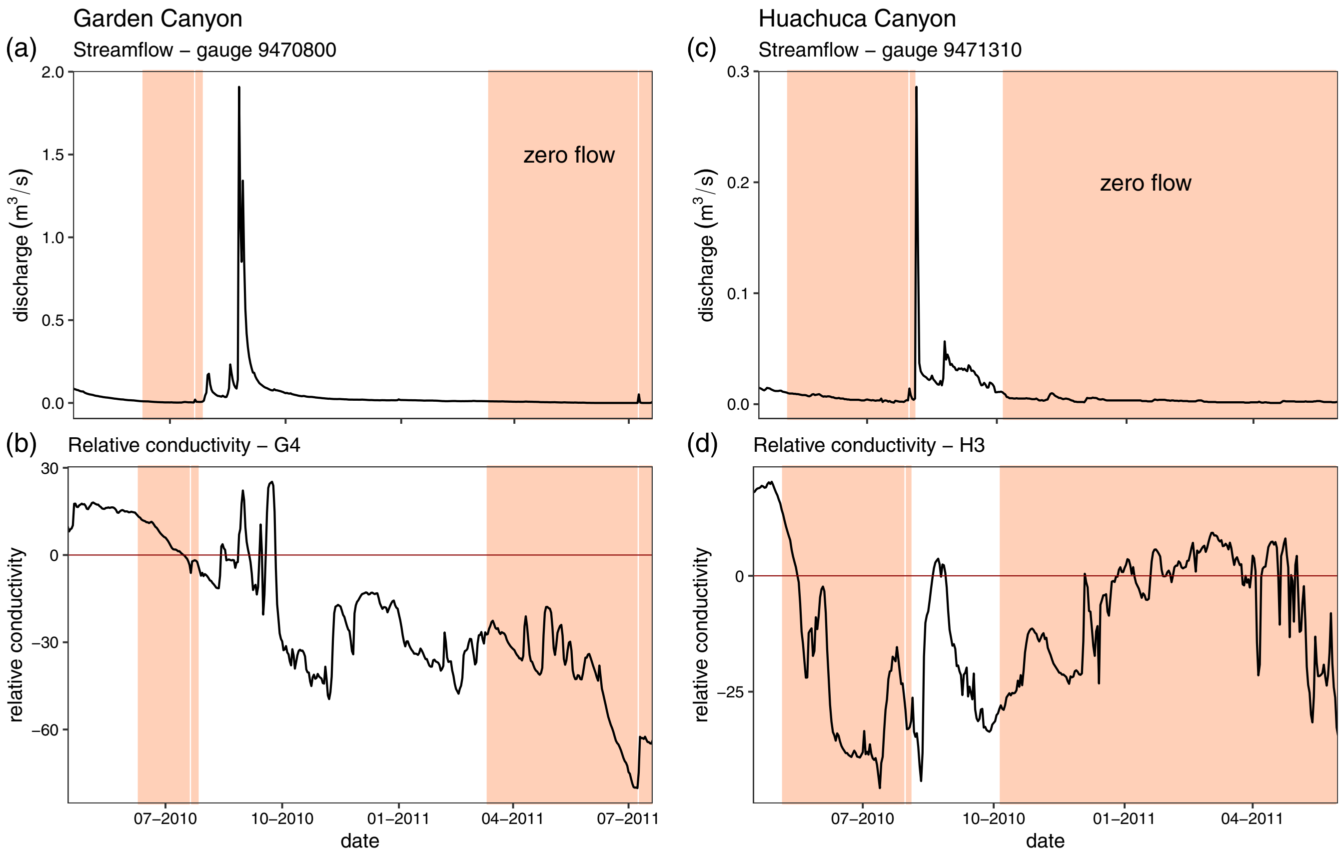

FIGURE 2 Discharge from USGS gauge (U.S. Geological Survey, 2022) and relative conductivity from sensors installed near gauge locations for streams in Garden Canyon (a, c), Huachuca Canyon (c, d) from June 2010 to May 2011. Shading highlights the periods of zero flow recorded at the USGS gauge (<0.01 m^3/s). Conductivity values above 0 (red horizontal line) indicate surface water presence [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Relative conductivity measured by the sensors and its translation to flow condition and simplified state used for seasonal classification. Flow condition is represented by a set color ramp through this paper

Relative conductivity	Flow condition	Color ramp	State for seasonal classification
≤ -90	dry		dry
> -90 and < 0	wet		wet
≥ 0	flow (or standing water)		

in each season. If the sensor measured flow or wet sediment for more than 50% of the season, then the whole season is considered "wet" for this sensor. All 37 sensors could then be assigned to one of six classes depending on when the stream reach is wet (always dry, wet during monsoon, wet during monsoon and autumn, wet during monsoon and winter, wet from monsoon to winter, always wet).

Underlying geology was also investigated for its association with local flow permanence; this was made possible based on the location of units with different permeability and fracturing (Goodrich et al., 2018; Larned et al., 2011; Levick et al., 2008). We used the hydrogeologic map and report from Brown et al. (1966), which provides information on geologic units, springs and faults across the Huachuca Mountains, to conduct a qualitative interpretation of the links between geology and flow condition. The hydrogeologic map, covering the north-east section of the Huachuca Mountains and the plain between the mountain front, the San Pedro River and the Babocomari River, was digitized by hand in QGIS and augmented with information on lithologic unit permeability (Sabathier & Jaeger, 2022).

3 | RESULTS

Canyons of the Huachuca Mountains display a diversity of flow patterns within and among streams, as well as a variable responsiveness to rainfall. ER sensor arrays provide opportunities to quantify streamflow variability in both space and time. Here we present the results as maps of flow condition distribution across the mountain front, distribution of sensors by ephemerality and daily time series of flow condition for individual sensors.

3.1 | Spatial and temporal variability of flow

Daily flow condition classification maps show aspects of spatial and temporal variability of flow condition across the landscape (Figure 3). The 2010 spring dry season (May–June) received its first rain on June 29. The number of sensors registering dry conditions increased from 70% on June 1st to 76% by June 13 (28 sensors out of 37, Figures 3a, 4a); we attribute the increase in dry sensors to moist sediments drying out. The sensors remained dry until June 30, the day following the first monsoon rain. We note that the five sensors that recorded surface flow remained steady throughout the season. During the three months of the monsoon (July to September), average rainfall increased to 3.3 mm/day, mostly falling in July and August with the strongest event registering 36.6 mm in a day (August 25, 2010) over the Huachuca Mountains (Figure 4a); all sensors registered flow or wet sediment on that day (Figure 3c), including 54% of sensors recording surface water. The sensors responded quickly to the August 25th event (Figure 4a), transitioning from 22% dry to all wet during the event. One stream never registered flow regardless of the volume of precipitation, and one sensor in Huachuca Canyon recorded surface water 97% of the year. Supplementary video S2 shows how the daily temporal and spatial distribution of flow condition change through the seasons across the mountain range (data for 2010) and the dynamic network expansion and contraction patterns.

Flow permanence was patchy in streams of the Huachuca Mountains, with alternating drier and wetter reaches (Figure 4). For example, in Blacktail Wash, the upstream sensor BT1 was never dry during the study period, while BT2 was fully dry for 97% of the year although they are less than 1 km apart. Blacktail Wash stayed wet during the monsoon and winter at the base of the mountain range (BT4 and BT5) but was mostly dry just 4 km downstream in the valley (BT6). In Huachuca and Garden Canyons, the driest reaches were located in downstream sections. The stream along Huachuca Canyon was wet close to the mountain top (H0, 1,900 mASL) and then showed patterns of drying downstream (H1 dried out 47% of the year and H2 dried out 56% of the year). At ~1,650 mASL, H3 and H4 are nearly perennial (no dry days) and the valley wash part of the stream heading toward the Babocomari River was the driest (H6 and H7). In Garden Canyon, most reaches responded directly to the monsoon, both at high and low elevation (G1, G5, G6, G7), while the mid-elevation (1,700 mASL) reaches are perennial (G2) or always remain wet (G4).

Stream reaches can be sorted by the temporal distribution of flow. Comparing the spatial distribution of flow against rainfall can

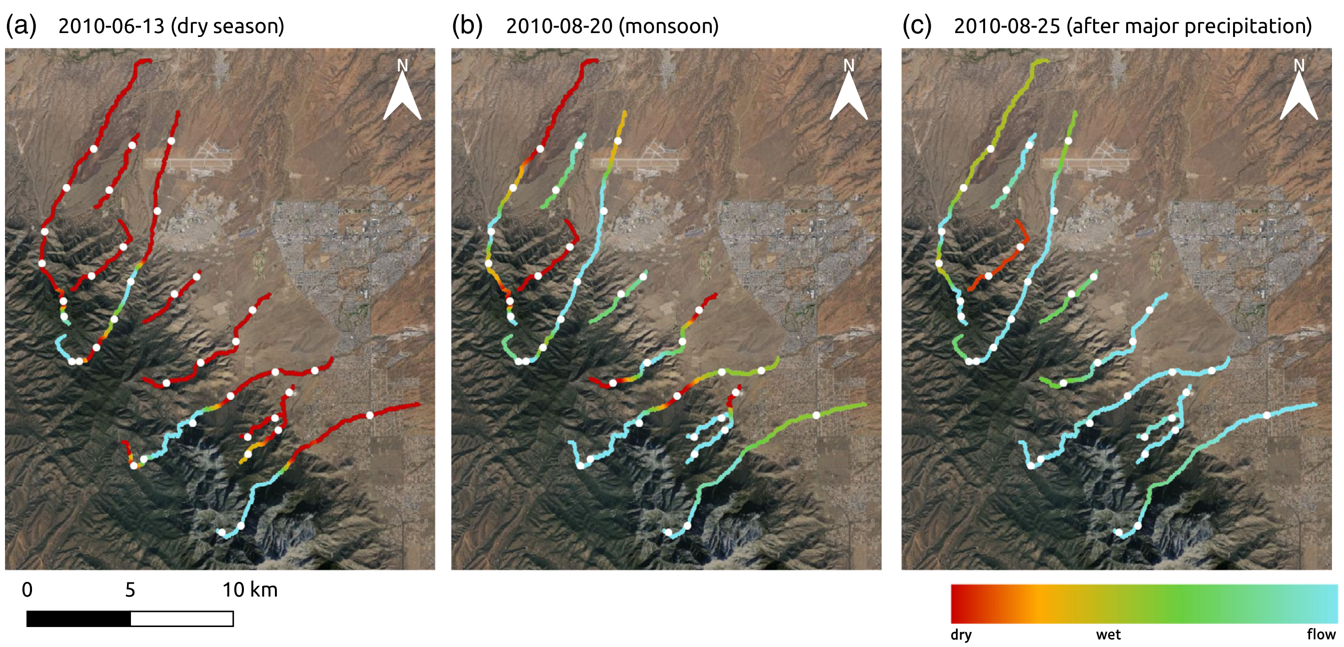

FIGURE 3 Maps of flow condition in the Huachuca Mountains based on inverse distance weighting interpolation from electrical conductivity sensors for three periods in time in 2010: dry season (a), monsoon (b) and monsoon right after a major storm (c). White dots represent sensor location. The interpolation between sensors is a visualization tool and does not represent the reality of flow between sensors. Flow lines are from the National Hydrograpahy Dataset (https://www.usgs.gov/national-hydrography/national-hydrography-dataset) [Color figure can be viewed at wileyonlinelibrary.com]

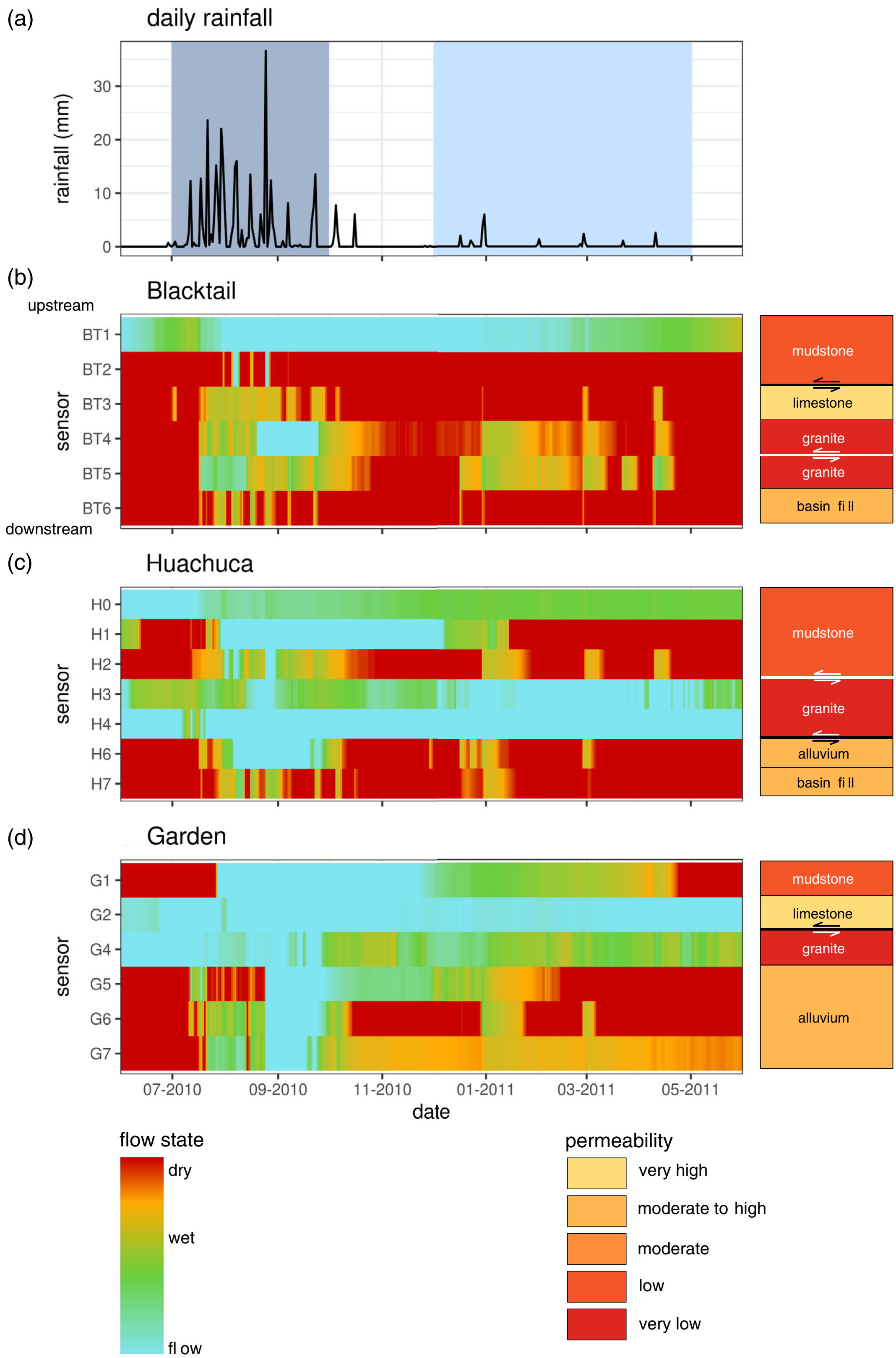

FIGURE 4 Daily rainfall (in mm) averaged over the Huachuca Mountains with the monsoon season shown as a dark gray rectangle and the winter shown as a light blue rectangle (a) and heatmaps of daily flow condition based on classified electrical conductivity measurement along Blacktail Canyon (b), Huachuca Canyon (c) and Garden Canyon (d). For each sensor, stacked along the y-axis from upstream (top of plot) to downstream (bottom of plot), flow condition is represented by color. On the right is the geology under each sensor (permeability to water represented by color) [Color figure can be viewed at wileyonlinelibrary.com]

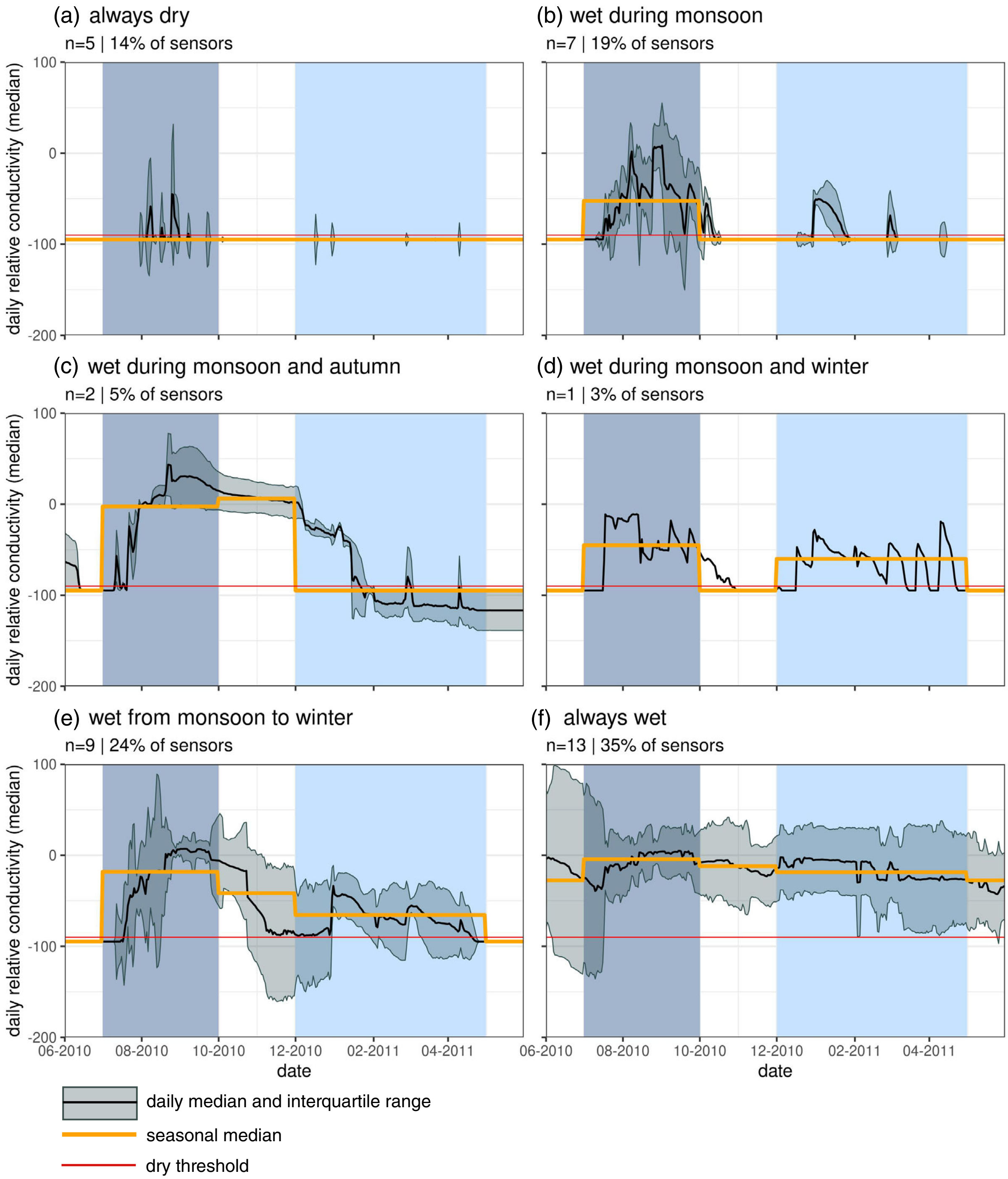

FIGURE 5 Time series of relative conductivity (daily median with interquartile range, seasonal median) for each seasonal class: always dry (a), wet only during the monsoon (b), wet during the monsoon and in autumn (c), wet during the monsoon and winter (only one sensor, d), wet from monsoon to winter (e), always wet (f). Dark gray shading highlights the monsoon season and light blue shading highlights the winter season. Conductivity values greater than −90 (red horizontal line) indicate wet flow state [Color figure can be viewed at wileyonlinelibrary.com]

also highlight the responsiveness of flow to precipitation. Figure 5 displays mean daily conductivity for each ephemerality class. There is no rainfall over the spring dry season (May–June). Precipitation increased to a total of 308 mm during the monsoon (July to September, dark gray rectangle) before declining to 19 mm during the dry autumn (October to November) and to 23 mm for the winter (December to April, light blue rectangle). The wide range of seasonal distribution of dry/wet cycles is shown in Figures 5a–f. The "always dry" (14% of sensors) and "always wet" (35% of sensors) classes are the most disconnected from rainfall, while other classes follow rainfall distribution patterns (get wetter during rainy seasons), though we notice that the monsoon is always the period with highest daily conductivity for all

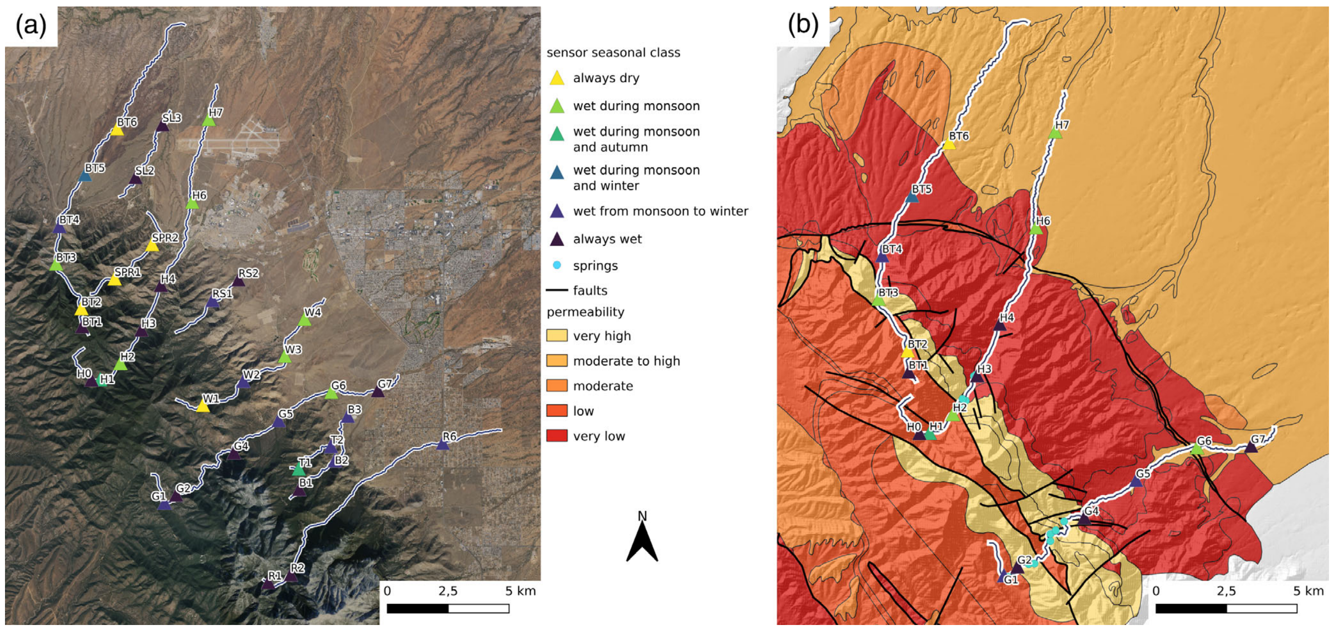

FIGURE 6 Map with location of conductivity sensors and their seasonal class (a). Hydrogeologic map with location of conductivity sensors and their seasonal class (for Blacktail (BT), Huachuca (H) and Garden (G) Canyons), location of springs and faults, and geologic units permeability to water (b). Seasonal class was established from sensors' measurements from June 1, 2010 to May 31, 2011 [Color figure can be viewed at wileyonlinelibrary.com]

classes, and the only period where values above 0 (surface water) were reached. Even the "always dry" reaches responded to the strongest monsoon events. On the opposite end of flow permanence, the spring season is dry for all classes except the "always wet" reaches, which still drop to their lowest conductivity before the first monsoon event.

Daily records of surface water presence recorded by the EC sensors were used to categorize each reach into a seasonal classification (Figure 6, Table 2). While 35% of the reaches (13 out of 37) remained wet year long, only one of them flowed the entire year, and five reaches were dry all year. Seven reaches wetted up only during the monsoon and remained dry for the rest of the year, while only one became wet during both the monsoon and winter rain season. Nine reaches were wet during the monsoon and remained so until the end of winter, even during the autumn dry season, while only two remained wet only during the monsoon and autumn dry season.

3.2 | Geology

While geology does not fully explain flow patterns, changes in subsurface formations translate into changes of surface flow. In Figures 4 and 6b, sensor locations and their seasonal ephemerality class are overlaid on the local geology, where each geological unit is characterized by its approximate relative permeability. Ephemerality classes do not appear to be organized along an elevation gradient or a north/south gradient. All three canyons displayed in Figures 4 and 6b start in mudstone, where permeability is low except along fractures, and the variability of flow patterns observed is high, from wet all year round (H0 and BT1) to always dry (BT2) (Figure 4a,c), even over short spatial scales. Limestone also displays this variability in water permeability, being highly permeable but also speckled with springs, especially along Garden Canyon (Figure 5b). As a result, G2 is always flowing while BT3 only flows during the monsoon (Figure 4a,c). Farther downstream, the impervious granite increases surface flow permanence, which is visible for sensors BT4 (wet in monsoon, autumn winter) and BT5 (winter in monsoon and winter) for Blacktail Canyon, as well as H3 and H4 (both wet all year) for Huachuca Canyon (Figure 6b). At the bottom of the mountain front, all three streams display a decrease in flow permanence with drier reaches. Streams reach the permeable basin fill that constitutes most of the valley and sensors are either dry all year long (BT6) or wet only during the monsoon (H7) (Figure 6b). They also never reach surface flow (Figure 4). Sensors H6, G5, G6 and G7 are on top of alluvium and only manage to reach surface water during the monsoon even if the sediment can stay wet longer (Figure 4).

3.3 | Interannual variability

Stream reaches react differently to interannual variations in rainfall, with some areas showing a steady behavior every year while others are more variable. Sensors G2, T1 and T2 recorded EC for 3 years (Figure 7) and exhibit the inter-annual variability of flow condition (from June 1, 2010 to May 31, 2013). The period 2010–2011 had a stronger monsoon and a drier winter than the following years. Rainfall total for the 2010 monsoon was 308 mm, against 236 mm for 2011 and 243 mm for 2012, while rainfall for

TABLE 2 Flow permanence (in proportion of days) for each season (dry spring, summer monsoon, dry autumn and winter), seasonal class and underlying geology feach sensor

			Flow permanence (% of days)				
Stream	**Sensor**	**Class**	**Spring**	**Monsoon**	**Autumn**	**Winter**	**Geology**
Brown	B1	Always wet	100	100	100	100	Granite
	B2	Monsoon to winter	0	78	100	57	Granite
	B3	Monsoon to winter	0	60	100	93	Stream alluvium
BlackTail	BT1	Always wet	100	100	100	100	Mudstone
	BT2	Always dry	0	13	0	0	Mudstone
	BT3	Monsoon	0	78	5	8	Limestone
	BT4	Monsoon to winter	0	83	82	80	Granite
	BT5	Monsoon and winter	0	83	43	74	Conglomerate + terrace deposits
	BT6	Always dry	0	39	0	5	Basin fill
Garden	G1	Monsoon to winter	0	72	100	95	Conglomerate
	G2	Always wet	100	100	100	100	Limestone
	G4	Always wet	100	100	100	100	Quartzite
	G5	Monsoon to winter	0	71	100	50	Stream alluvium
	G6	Monsoon	0	86	25	25	Stream alluvium
	G7	Always wet	51	82	100	100	Stream alluvium
Huachuca	H0	Always wet	100	100	100	100	Mudstone
	H1	Monsoon and autumn	20	81	100	30	Mudstone
	H2	Monsoon	0	88	46	34	Mudstone
	H3	Always wet	100	100	100	100	Granite
	H4	Always wet	100	100	100	100	Granite
	H6	Monsoon	0	83	21	25	Stream alluvium
	H7	Monsoon	0	53	12	24	Basin fill + terrace deposits
Ramsey	R1	Always wet	100	100	100	100	Limestone
	R2	Always wet	77	100	100	85	Limestone
	R6	Monsoon to winter	0	75	90	56	Basin fill + terrace deposits
Rock spring	RS1	Monsoon to winter	0	77	64	70	Granite
	RS2	Always wet	61	80	100	100	Granite + terrace deposits
Slaughter house	SL2	Always wet	51	83	100	100	Conglomerate
	SL3	Always wet	51	85	100	100	Basin fill + terrace deposits
Split rock	SPR1	Always dry	0	1	0	0	Granite
	SPR2	Always dry	0	23	7	14	Granite
Tinker	T1	Monsoon and autumn	0	86	100	46	Granite
	T2	Monsoon to winter	16	88	100	100	Granite
Woodcutters	W1	Always dry	0	13	0	0	Granite
	W2	Monsoon to winter	41	91	100	100	Granite
	W3	Monsoon	0	85	20	21	Granite + terrace deposits
	W4	Monsoon	0	55	13	20	Basin fill

the 2011 winter was 23 mm against 65 mm in 2012 and 75 mm in 2013 (Figure 7a). Sensors G2 (Figure 7b) and T2 (Figure 7d) recorded a steady pattern across all 3 years of record despite interannual variability in precipitation. G2 (located at the mountain top) kept flowing through the whole period (Figure 7b) and T2 (mountain front) maintained a "wet from monsoon to winter" pattern, only drying up during the spring dry season, although this reach slowly dried up over the 2011 winter, while it maintained surface water in 2012 and 2013 (Figure 7d). Sensor T1 (mountain front) displayed more variability year to year without following a specific trend. It sustained flow through the 2010 monsoon and autumn, then shifted to a flashier pattern in 2011 with cycles of

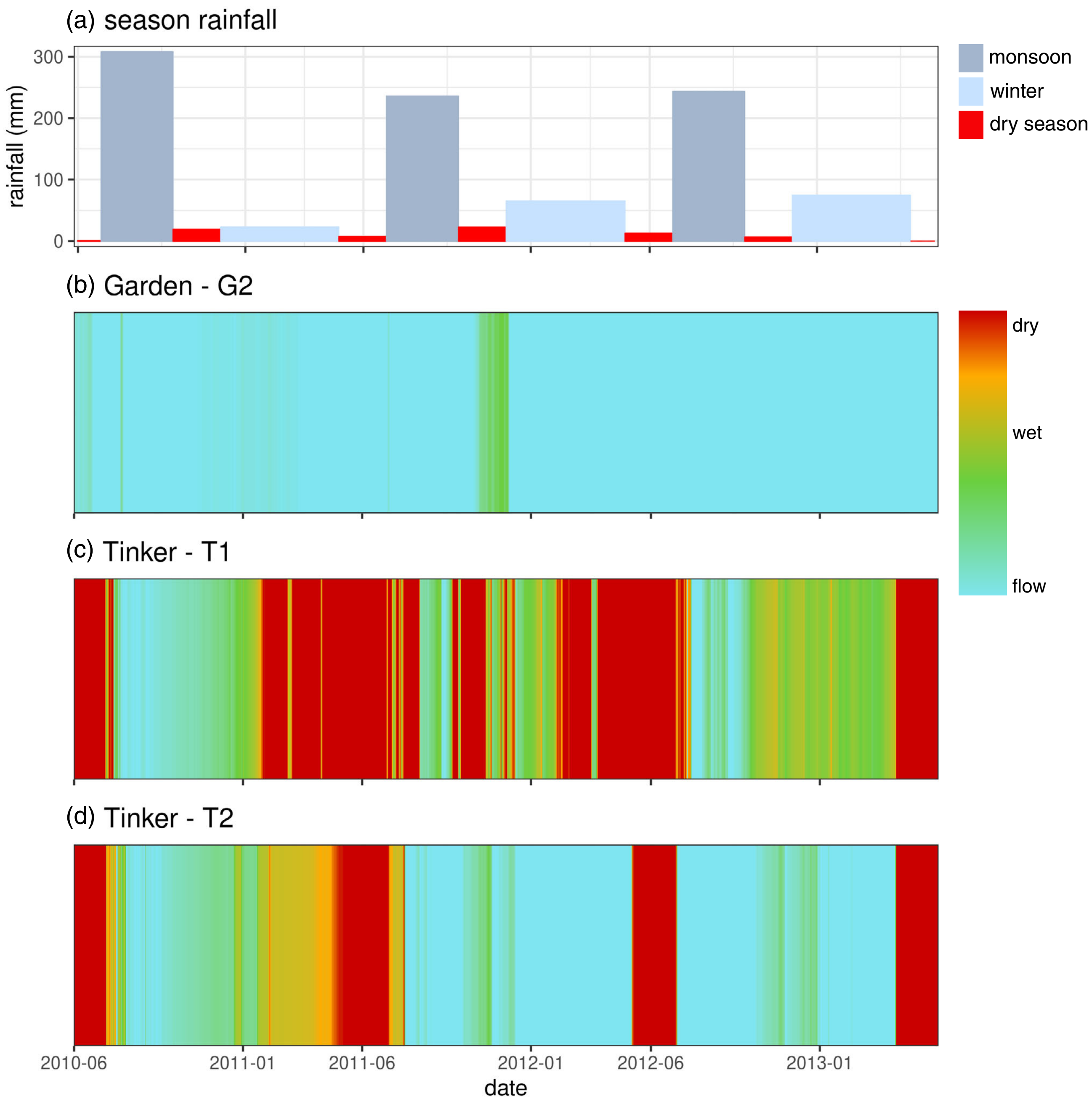

FIGURE 7 Seasonal rainfall (in mm) averaged over the Huachuca Mountains with the monsoon season shown as in dark blue, winter in light blue rectangle, spring and autumn dry seasons in red (a) and heatmaps of daily flow condition based on classified conductivity measurement for G2 (b), T1 (c) and T2 (d), from June 1, 2010 to May 31, 2013 [Color figure can be viewed at wileyonlinelibrary.com]

drying/re-wetting, before going back to remaining wet from monsoon to winter in 2012 (Figure 7c).

4 | DISCUSSION

Non-perennial streams in drylands are important sources of moisture and hotspots of biodiversity (Bogan et al., 2015; Datry et al., 2014; Larned et al., 2010). As such, understanding the timing and distribution of flow is critical for mapping habitats and their potential climate change vulnerability (Price, Jones, Hammond, Zimmer, & Zipper, 2021). In this paper, we demonstrate how electrical conductivity sensor data can be used to map distribution of surface water and channel sediment moisture at high spatiotemporal resolution in small non-perennial streams. This information can then be used to classify stream reaches by seasonal patterns, a useful metric to summarize the temporal variability of flow in a way that can be compared to climate patterns and related to wildlife and vegetation dynamics. The uncertainty caused by the lack of calibration and the use of a relative conductivity prevents us from determining the exact timing and period of flow, but the use of a continuous scale and a general classification based on seasons, allows us to identify broad differences in timing of flow between sensors. In future studies, sensors should be calibrated by being put in wet and dry environments in controlled conditions to establish which values are linked to a specific moisture state before being deployed in the field (Adams et al., 2006).

4.1 | Spatial and temporal variability of flow

Streams of the Huachuca Mountains display high variability of flow, both through time and space, with alternating wet and dry reaches. Most reaches are very sensitive to rainfall and only flow during the monsoon and/or the winter rain season, while others remain constant (always dry or always wet) no matter the precipitation input (Gallo et al., 2020). The light winter precipitation and melting snow (low intensity and long duration) travels more slowly and has greater potential to infiltrate into the ground and feed the many springs that supply the perennial reaches (Stromberg et al., 2015), while the intense monsoon storms (high intensity, high frequency, and short duration) are more likely to initiate overland flow in the canyons (Levick et al., 2008; Stromberg et al., 2015). Non-perennial reaches can be more or less responsive to rainfall. Some reaches get wet both during monsoon and winter, responding to the smallest precipitation events, and others that need significant rain falling in a short period only flow during the monsoon.

Despite the small sample size and the limited number of parameters investigated in this study, we can still combine our findings and the literature to identify the potential controls on flow permanence in these canyons. The reaches that exhibit wet sediment or flow during the monsoon and stay wet through the dry autumn and to the winter are likely fed by local aquifers that manage to fill up during the monsoon. For example, flatter areas can allow for seepage into the local aquifer to feed the stream downstream, and faults form preferential paths for groundwater drainage to springs (Lovill, Hahm, & Dietrich, 2018; Martin, Kampf, Hammond, Wilson, & Anderson, 2021). Areas sheltered by vegetation or the surrounding topography might also stay wet longer, as evaporation is reduced. As for the reaches that remain dry, we noticed that they were either on top of permeable sand and gravel layers or colluvium.

4.2 | Geology and additional controls

Streams in the Huachuca Mountains, as is true in other ephemeral streams of the Southwest USA, show abrupt longitudinal changes in flow permanence influenced by geomorphological processes and discontinuities (Goodrich et al., 2018; Larned et al., 2011; Lovill et al., 2018). An example of how water moves downstream along Huachuca Canyon is shown in Figure 8. Geology can alter surface hydrology through permeability of underlying formation, spring location, perched aquifers, faults, fractures or sediment deposits (Levick et al., 2008). The headwaters of the streams studied here are mainly located on top of mudstone and sandstone, before meeting limestone. Flow permanence on top of these layers is variable, going from reaches that are always dry to always flowing. This behavior could be explained by the fact that the mudstone units of the Huachuca Mountains are impervious layers but intersected by small fractures that

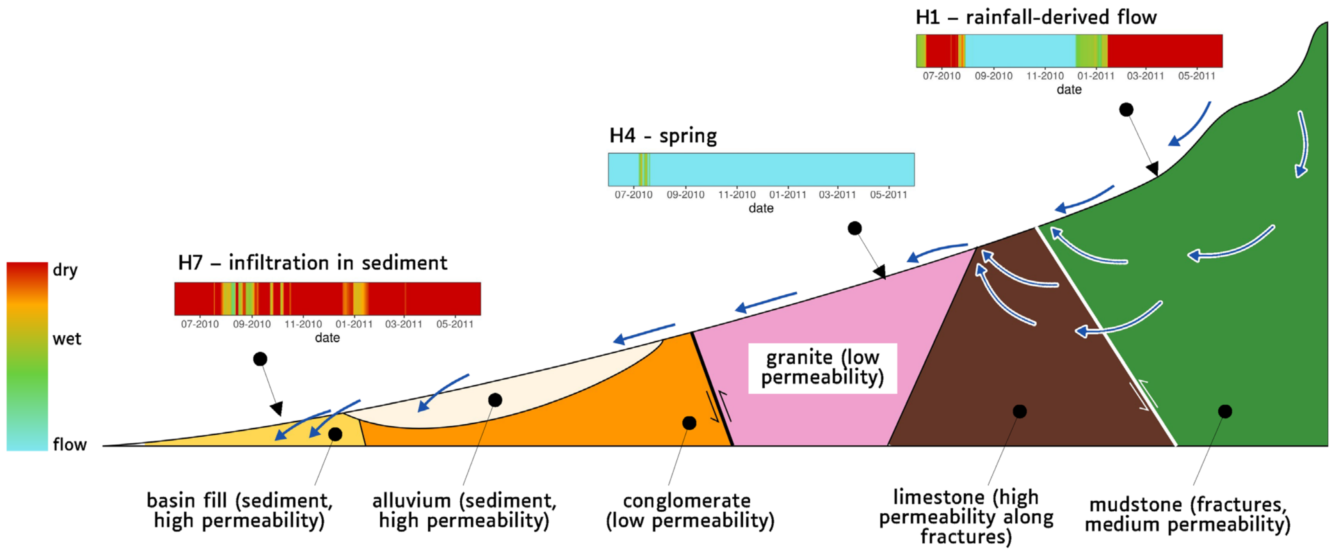

FIGURE 8 Conceptual model of flow distribution along Huachuca Canyon and water travel downstream (overground and underground), with the location and daily records of three conductivity sensors from June 1, 2010 to May 31, 2011 (from upstream to downstream: H1, H4, H7). Water (blue arrows) seeps in fractured mudstone and limestone before reaching the surface when encountering impervious units (granite) and faults. At the bottom of the mountain front, water travels down in permeable sediment layers to reach the regional water table [Color figure can be viewed at wileyonlinelibrary.com]

collect water, which is then released to springs and streams, while the very high permeability of limestone, due to a high density of fractures and solution channels, is interrupted by impervious siltstone beds (Brown et al., 1966). This upper area of the mountains is also dissected by faults that form preferential flow paths for water. The diversity of structures, each with their own permeability to water, in part, leads to the diversity of flow permanence patterns we see along the canyons. The lower half of the mountain range is underlain by quartzite and granite and it is on top of these impermeable bedrock units that we observed an increase in flow permanence in our canyons and where most of the perennial flow occurs. Down in the San Pedro River basin, water travels over the low permeability conglomerate before reaching the sand and gravel of the sedimentary basin fill that form a highly permeable fan around the Huachuca Mountains (Brown et al., 1966). This is the area with some of the driest reaches in our study. Rainfall distribution is also highly dependent on elevation, with higher areas receiving more rainfall and lowland stream reaches receiving lower precipitation. Monsoon storms can also cover small extents and might cover only one watershed, bringing water to one canyon while its neighbors remain dry.

Local channel conditions and human activity can override expected geologic response at local scale. Channel geometry and stream channel density, itself dependent on grain size and sediment composition, are important reach-scale controls on flow permanence and streambed sediment moisture (Gallo et al., 2020; Larned et al., 2010; Pate, Segura, & Bladon, 2020; Whiting & Godsey, 2016). Some sensors, such as BT2, were dry no matter the underlying geology; a result likely due to a thick and very permeable sediment layer in the streambed. There are also anthropogenic controls on flow permanence in the Huachuca Mountains. The streams of Garden and Huachuca Canyons have historically been used as a water source for the U.S. Army Installation Fort Huachuca. Spring boxes and pipes are still redirecting water down to the fort (Brown et al., 1966). Some downstream reaches are in urban areas, which can also affect flow regimes. Artificial impervious surfaces prevent rainwater from seeping through the sediment and redirect it instead to the non-perennial washes, which leads to flow being present more often and for longer periods (Gungle, 2006).

4.3 | Interannual variability

Response to inter-annual variations in rainfall was also variable, with some stream reaches demonstrating consistent flow patterns every year while others fluctuated more. Reaches likely fed by springs, such as G2, show little variation and remained flowing through the dry seasons and weak winter rains. Sensor T2 also recorded a regular pattern, only fully drying up during the spring dry season, but the weak winter rain of 2011 led to a progressive dry up while stronger precipitation in winter for 2012 and 2013 seems to have managed to keep that reach flowing until the spring dry season. The flow pattern for T1 is less regular but we note that a weak winter rain season led to an early dry-up in 2011 and that weaker monsoons in 2011 and 2012 might be the cause of the shorter period of surface flow. Due to the uncertainty in the link between relative conductivity value and flow condition, precise timing of shifts between dry and wet sediment, or wet sediment and flow is imprecise and might explain some of the interannual variability.

4.4 | Implications for conservation

Conductivity analysis demonstrated in this paper could be an important tool for mapping potential habitats for species of conservation interest. The key elements that make this work useful are its high temporal resolution (daily data in remote areas with complex topography, which makes fieldwork time-consuming), high spatial resolution (we are able to measure flow state at a precise location), and the fact that the high number of sensors spread across and along streams provide a landscape-scale overview of temporal and spatial distribution of moisture and flow across a whole mountain front. The dataset provides information on sediment moisture and surface flow, but also on which state is reached when, and how often. This record of spatio-temporal distribution of flow and soil moisture supports efforts to pinpoint reaches of perennial flow (such as H4 or G2) in an otherwise dry region. Reaches that manage to remain wet during the dry spring (all sensors in the "always wet" class) can play a critical role as moist and cool refuges. Once flow resumes in the drier reaches and the stream network connects, animals that had found shelter in the perennial reaches can re-colonize the whole network (Bunn, Thoms, Hamilton, & Capon, 2006; Larned et al., 2010). They can also be favorable habitats for species such as the Huachuca water umbel (*Lilaeopsis schaffneriana ssp. Recurva*), an herbaceous, semi-aquatic perennial plant which needs a permanently wet environment (Bagne & Finch, 2013). For non-perennial reaches, we are able to compare the limited periods of sediment moisture or surface water to the phenology of species of interest. The Chiricahua Leopard Frog (*Lithobates chiricahuensis*) can be found in temporary streams that dry periodically to discourage non-native predators and competitors while still staying moist enough for the frogs and with surface water for breeding, the breeding period depending on elevation (Bagne & Finch, 2013). A host of other amphibian species in the region are dependent on the patchwork of water availability (Mims, Phillipsen, Lytle, Kirk, & Olden, 2015), as are aquatic invertebrates (Phillipsen et al., 2015). Being able to map the distribution of flow across the landscape could also be used to highlight potential wet corridors for allowing species dependent on sediment moisture and surface water to travel between favorable habitats and breeding locations. Data on flow permanence can be paired with wildlife and vegetation surveys (through camera traps, bioacoustics, or remote sensing for example) to study flow permanence as a parameter in habitat mapping and species distribution.

Riparian and semi-aquatic species in the study region are considered highly vulnerable to climate change (Bagne & Finch, 2013), so recording the flow condition in streams for several years could be a useful tool for detecting areas that are particularly sensitive to variations in rainfall and/or moisture. A shift in rainfall distribution, timing and intensity could, for example, change the distribution of seasonal water patterns across the landscape and create ecological shifts for communities depending on specific flow regimes (Bogan et al., 2015; Jaeger et al., 2014; Stromberg, 2013). Depending on the controls governing the presence of water in a reach, areas might be more or less sensitive to climate change. In reaches that are more sensitive to precipitation, a dry winter might lead to an earlier drying of a stream that usually flows until spring. A non-perennial stream that only responds to monsoon rains (wet during monsoon class, sensors H6 and G6 for example) might be very responsive to a stronger or weaker monsoon, while reaches sustained by groundwater inputs (always wet class, sensor BT1 or G2 for example) might be better buffered and could remain wet, affirming their critical status as refuge for drought-sensitive species (Gallo et al., 2020; Stromberg et al., 2015). Springs are the areas most likely to provide a steady water source to the surface, but they are reliant on sufficient water inputs in upstream locations that replenish the local aquifers. Thus, severe changes in rainfall regimes could also lead to shifts even in the wettest perennial reaches (Van Loon, 2015). The vegetation and wildlife in these always wet reaches might also be more severely impacted, as they are adapted to a perennial water source, and a temporary dry-up could lead to changes in riparian forest extent and shift in species. Increases in dryness could also lead to a loss of connectivity, with flowing reaches becoming less frequent and more isolated (Jaeger & Olden, 2012; Seager et al., 2013).

5 | CONCLUSIONS

We documented the spatiotemporal variations in flow permanence and channel substrate moisture in the temporary streams of the Huachuca Mountains (southeastern Arizona, USA). We distinguished between reaches highly responsive to local climate and those with more stable flow patterns. Although climate is the first control on water distribution at the regional scale, we revealed that underlying geology, as well as other localized factors such as streambed composition and landscape topology, affect flow permanence locally. Our work shows how the high spatial and temporal resolution provided by electrical conductivity sensors can be used to build a local, reach-scale understanding of surface flow permanence and distribution by using a seasonal classification of flow patterns, and how the resulting. The resulting local, reach-scale understanding of surface water distribution can then provide critical information on potential habitat for riparian species and these habitats' sensitivity to climate change.

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Streamflow data courtesy of the U.S. Geological Survey (2022). PRISM Precipitation data provided by PRISM Climate Group, Oregon State University, https://prism.oregonstate.edu.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in ScienceBase at https://doi.org/10.5066/P90K3SIL. Daily electrical conductivity sensor data and the digitized geology layer following Brown et al. (1966) are found in Sabathier and Jaeger (2022).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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