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SENSITIVITY OF INTERMITTENT STREAMS TO CLIMATE VARIATIONS IN THE USA

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ABSTRACT

There is a great deal of interest in the literature on streamflow changes caused by climate change because of the potential negative effects on aquatic biota and water supplies. Most previous studies have primarily focused on perennial streams, and there have been only a few studies examining the effect of climate variability on intermittent streams. Our objectives in this study were to (1) identify regions of similar zero-flow behaviour and (2) evaluate the sensitivity of intermittent streams to historical variability in climate in the USA. This study was carried out at 265 intermittent streams by evaluating (1) correlations among time series of flow metrics (number of zero-flow events, the average of the central 50% and largest 10% of flows) with climate (magnitudes, durations and intensity) and (2) decadal changes in the seasonality and long-term trends of these flow metrics. Results identified five distinct seasonality patterns in the zero-flow events. In addition, strong associations between the low-flow metrics and historical changes in climate were found. The decadal analysis suggested no significant seasonal shifts or decade-to-decade trends in the low-flow metrics. The lack of trends or changes in seasonality is likely due to unchanged long-term patterns in precipitation over the time period examined. Published 2015. This article is a U.S. Government work and is in the public domain in the USA.

KEY WORDS: intermittent streams; climate change; classification; ephemeral streams

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INTRODUCTION

Intermittent streams (streams that cease to flow for any duration of time) are common in many parts of the world and are estimated to comprise about 60% of total stream length in the USA (Levick et al., 2008). Although intermittent streams are ubiquitous, most are not monitored by streamflow (henceforth, referred to as flow) gauges. In addition to being widespread, intermittent streams serve critical roles in the water cycle. They provide recharge to aquifers and transfer melt water from ice and snow to perennial streams. They collect and route flood waters and flows that can be used for irrigation and other water supplies, and they also can accumulate agricultural and municipal effluents. Lastly, the role of intermittent streams in maintaining riparian flora and aquatic biota is a matter of much current interest (e.g. Feminella, 1996; Bonada et al., 2007; Stromberg et al., 2007; Chakona et al., 2008; Arscott et al., 2010; Stromberg et al., 2010; García-Roger et al., 2011). For example, intermittent streams often act as aquatic invertebrate egg and plant seed banks and may collect large amounts of organic material that allow for dispersal of biota downstream that maintains biological diversity (Steward et al., 2012).

Direct-human modifications to landscapes and/or stream morphologies, such as conversion of land from forest to agriculture or dam construction, have been found to alter the natural behaviour of intermittent streams (e.g. McMahon and Finlayson, 2003; Fu et al., 2004; Qi and Luo, 2005; Hao et al., 2008; Levick et al., 2008; Roy et al., 2009; Larned et al., 2010). Changes in climate also can alter the flow characteristics of intermittent streams (e.g. Larned et al., 2010; Steward et al, 2012), with particular concern emerging that future changes in climate may cause significant changes in flow characteristics (e.g. Arnell, 2003; Milly et al., 2005). Döll and Schmied (2012), for example, have predicted substantial numbers of perennial streams transitioning to intermittent streams, and vice versa, under a greenhouse gas emission scenario from the Intergovernmental Panel on Climate Change (IPCC) (Nakicenovic and Swart, 2000). Jaeger *et al.* (2014) also predict the frequency of zero-flow days to increase and flowing portions of the stream to decrease for the Verde River basin in Arizona under a RCP8.5 gas emission scenario by IPCC (van Vuuren et al., 2011). Polade *et al.* (2014) project that the number of days with no precipitation will substantially increase over many basins globally based on 28 coupled general circulation models from the CMIP5 experiment (Taylor et al., 2012) under the RCP8.5 gas emission scenario. Due to the great deal of interest in the literature regarding climate-change effects on flow regimes, we examine the impact of historical climate variability on intermittent streams.

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Our objectives in this study were to (1) identify regions of similar zero-flow behaviour and (2) evaluate the sensitivity of flow metrics for these types of intermittent streams to historical variability in climate in the USA. Specifically, we analysed numbers of zero-flow days, the central 50% flow ranges and the largest 10% of flows in selected intermittent streams to (1) assess the sensitivity of these intermittent streams to climate variations and (2) determine if there have been long-term shifts in the timing and/or intensifying/abating of the median portions and extremes of flow regimes in intermittent streams.

DATA AND STUDY AREA

Annual time series of three flow metrics were calculated from daily-flow records for selected streams: the number of zero-flow days, the average of the central 50% range of flows and the average of the largest 10% of flows. An annual time-step was selected because it has been found to be associated with ecological impairment in intermittent streams (Davey et al., 2006; Datry et al., 2007; Arscott et al., 2010). Daily-flow values were downloaded from the U.S. Geological Survey National Water Information System by using a batch programme by Granato (2008). Variations and trends in the three flow metrics were evaluated in the context of corresponding historical variations in basin average monthly temperature and precipitation estimated by the PRISM Climate Group (http://www.prism.oregonstate.edu/).

In addition, daily precipitation data for 1060 meteorological stations distributed throughout the USA (Easterling et al., 1999) were analysed to evaluate relations between the flow metrics and precipitation at the sub-monthly time scale. These data were obtained from the Carbon Dioxide Information Analysis Center (CDIAC) at Oak Ridge National Laboratory in Oak Ridge, Tennessee. The CDIAC data were used to calculate point values for the average storm intensity, average storm duration and average interstorm period. The point values of the climate characteristics were interpolated onto a 5-km resolution grid for the conterminous USA by using ArcInfo. Grid cells that did not correspond in space to a point measurement of climate were assigned the climate characteristic values of the nearest meteorological station.

Intermittent streams were selected from the GAGES2 database of streams developed by Falcone (2011). GAGES2 contains data on natural characteristics (e.g. climate, topography, soils and geology) and human impacts (e.g. land use and reservoirs) for 9067 basins in the USA; the database also includes a designation of each stream as 'reference' (i.e. minimally impacted by direct-human modifications) or altered from reference conditions. For the first objective of determining regions of similar intermittent zero-flow behaviour, the criteria for stream selection were (1) classification as a reference stream; (2) a minimum length of record of 10 years between 1950 and 2012 and (3) a minimum annual average over the entire period of record of at least 15 days of zero flow per year. The last criterion eliminated streams that seldom go dry. The 15-day threshold was determined by examining the distribution of the average number of zero-flow days for all reference streams in GAGES2 that have at least 1 day of zero flow in their records. Application of these criteria resulted in the selection of 265 intermittent streams in the USA (Figure 1a) and the exclusion of 304 streams. An initial assumption was that flow metrics calculated by using short periods of record (<30 years) were not statistically different from those based on longer records. The second objective of assessing the sensitivity of intermittent streams to climate required the use of 'long-term' intermittent streams. As a result, the second criterion was adjusted to a minimum of 48 years of record resulting in a subset of 57 long-term intermittent streams. The previous assumption would be tested by using the long-term intermittent streams.

METHODS

For the first objective of identifying regions of similar zero-flow behaviour, the entire period of record at the 265 intermittent streams was used to calculate the percent occurrence of zero-flow days occurring in each month of the year creating a time series. A *k*-means cluster analysis was then applied to the time series of percent occurrence values using the '*k*means' function in MATLAB. The *k* values that were tested were 2, 3, 4, 5 and 6. The final *k* value was chosen based on visual inspection of percent occurrence plots for each group, and the degree to which each group was spatially clustered. A final inspection was performed to see if any minority patterns in the time series were incorrectly assigned and, if so, they were reassigned either to a new group or another existing one. Groups that geographically spanned different portions of the study area that had differing precipitation patterns were further subdivided based on these patterns. Visual inspection of six monthly time series of precipitation averaged on a decadal time step (1950 to 1959, 1960 to 1969, 1970 to 1979, 1980 to 1989, 1990 to 1999 and 2000 to 2012) was used to identify these precipitation patterns. It was assumed that the precipitation patterns would influence the flow behaviour of intermittent streams.

Three methods were used to evaluate the sensitivity of flow metrics to variability in climate. For these three approaches, the 58 long-term intermittent streams were used. In the first approach, a moving 10-year averaging window was applied to the annual time series of the three flow metrics and the PRISM climate variables. This averaging window was used to remove noise from the time series, as well as allow better representation of possible delayed influences

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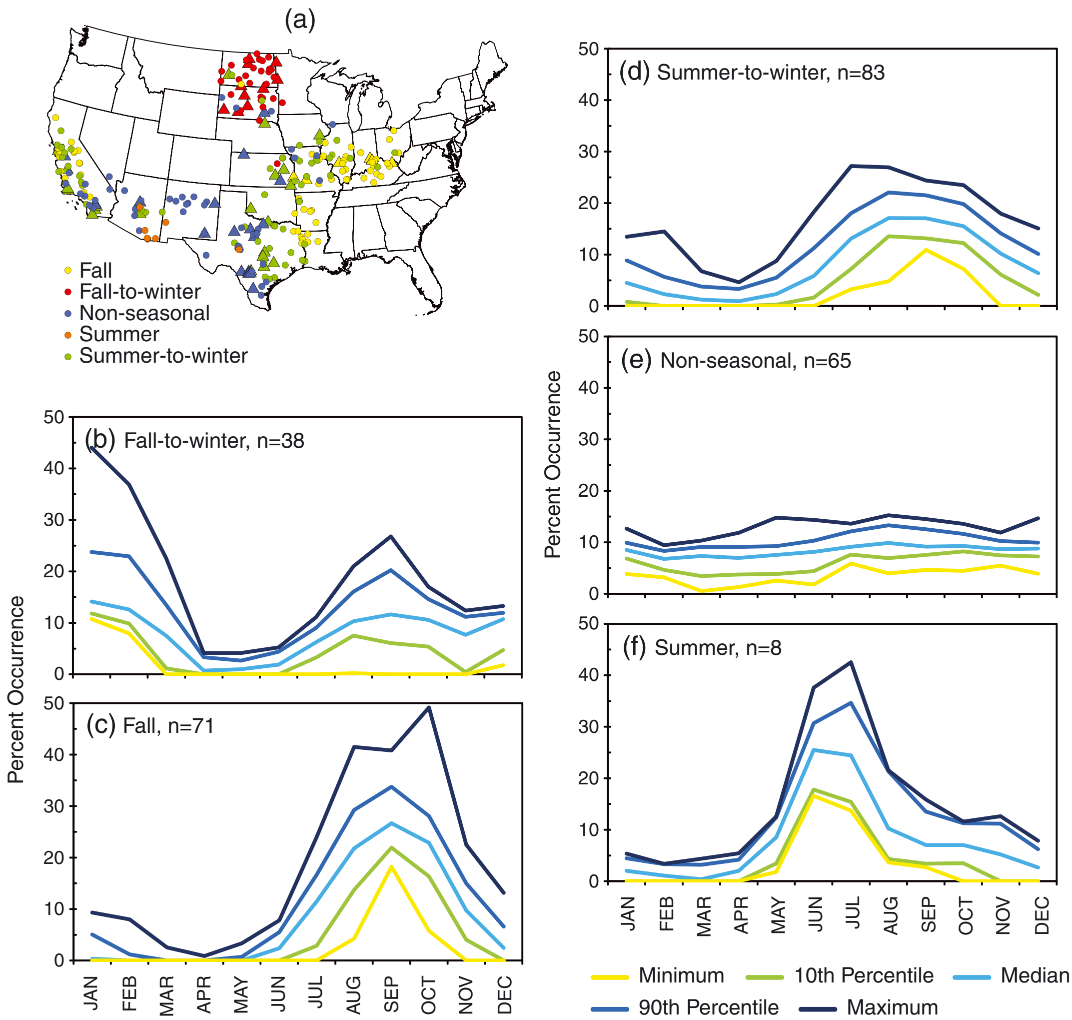

Figure 1. (a) Coloured dots (>10 and <48 years of record, $n = 208$) and triangles (>=48 years of record, $n = 57$) represent U.S. Geological Survey streamgauges on 265 intermittent streams. The colours represent the five general patterns of timing regarding when the zero-flow values occurred during the calendar year: fall (yellow), fall-to-winter (red), non-seasonal (blue), summer (orange) and summer-to-winter (green) intermittent streams. Percent occurrence of zero flows calculated over all gauges in each class and all years between 1950 and 2012 for (b) fall-to-winter, (c) fall, (d) summer-to-winter, (e) non-seasonal and (f) summer intermittent streams. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

of groundwater discharge to the streams in response to antecedent, prolonged precipitation variations. *Z*-score values were calculated for these smoothed time series (each 10-year average value was subtracted from the long-term mean and divided by the standard deviation), and Pearson correlations were calculated between the flow and climate variables.

In the second approach, all zero-flow days were grouped into roughly 10-year blocks: 1950 to 1959, 1960 to 1969, 1970 to 1979, 1980 to 1989, 1990 to 1999 and 2000 to 2012. For each 'decade', the percent occurrence of zero-flow days occurring in each month of the year was calculated for each stream. Graphs of the percent occurrence of zero-flow days in each month were plotted and inspected for intensifying, abating or earlier/later shifting of zero-flow dates during recent decades (e.g. if the lowest percentage of zero-flow events occurred in September and in a following decade shifted to October). A similar method was applied to the percent occurrence of the largest 10% of non-zero flows, and similarly for the percent occurrence of the non-zero flows that were less than the largest 25% of flows but greater than the lowest 25% of non-zero flows (a measure of central tendency of the flow regime). Each beginning and ending year of every 10-year block was shifted later by 5 years (except for the last block that still ends in 2012), and a second set of flow metrics was calculated to see if the analysis was sensitive to the arbitrary selection of start and end years of the 10-year blocks.

The third approach evaluated the stability of the frequency distribution of flows to decadal wet and dry periods. In addition, this approach would address the assumption

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used in identifying regions of similar zero-flow behaviour that the flow metrics calculated from short periods of record were not statistically different from those based on longer records. This evaluation involved comparisons of calculated flow percentile values (99, 90, 85, 80, 75, 70, 65, 60, 55, 50, 45, 40, 35, 30, 25, 20, 15, 10, 5 and 1) for each 10-year block mentioned earlier to percentile values based on all years of record excluding that 10-year block at each intermittent stream (six comparisons × 57 intermittent streams = 342). A two-sample Kolmogorov–Smirnov test was used to test the null hypothesis that the two different sets of flow percentile values were drawn from the same population using a $\alpha = 0.05$ and 0.20 (Massey, 1951).

The last approach related flow variables to precipitation variables derived from daily precipitation data. The mean-monthly duration of consecutive days with precipitation (wet periods), consecutive days with no precipitation (dry periods) and intensity of daily precipitation estimates were compared to the concurrent monthly percent occurrence values of the number of zero flows and the average of the largest 10% of flows. Pearson correlations were calculated among the three climate metrics and both flow metrics for the 265 intermittent streams.

RESULTS

The *k* value chosen in the *k*-means clustering method was 4; this value produced groups of similar percent occurrence of zero-flow events that were spatially clustered. After visual inspection, it was determined that eight intermittent streams were misclassified, and they were placed into a new group because all of them shared a similar pattern in their time series of percent occurrence values, and they were spatially clustered. There were no long-term intermittent streams (streams with period of records greater than or equal to 48 years) among these eight, so this group was excluded from any analysis that used long-term intermittent streams, such as the seasonal characteristics analysis. The five different groups identified as being distinct in terms of seasonality of zero-flow periods were the following: fall, fall-to-winter, non-seasonal, summer and summer-to-winter intermittent streams (Figure 1a). The non-seasonal and summer-to-winter streams were further subdivided into three subclasses, and the fall groups were subdivided into two subclasses by visually inspecting precipitation patterns at each site. This process allowed us to subdivide the sites into streams with highest precipitation in spring/summer, streams with highest precipitation in fall/winter (not present in the fall intermittent streams) and streams with the highest precipitation in winter months.

Figures 2a, 2b, 2c and 2d show the long-term variations of *Z*-score values for the three flow metrics and precipitation for four sites representative of four types of intermittent streams. The summer intermittent streams included no long-term streams, so this group was excluded from the long-term analysis. For the most part, the three flow metrics were strongly correlated to precipitation for the four different stream types. Figure 2e shows the Pearson correlation values among the *Z*-score time series for the flow and climate metrics for the 57 intermittent streams. The results in the table do not reflect differences among the stream classes, that is, all the sites were combined into a single group for each metric. The average of the central 50% range of flows and largest 10% of flows was strongly correlated to precipitation. The number of zero flows had a strong negative association with precipitation. Notably, historical temperature variations played no significant role in the decadal scale fluctuations of the three flow metrics considered in these intermittent streams (Figures 2e, 3 and 4).

Long-term and seasonal characteristics of the decadal flow metrics and precipitation averages are shown in Figures 3 and 4 for the four primary types of intermittent streams, including the seven subsets of non-seasonal and summer-to-winter dominated streams mentioned earlier. One subset of fall intermittent streams was not included in this analysis because there were no long-term streams in the western portions of the study area that had highest precipitation occurring during winter months. Generally, the overall seasonality of the three flow metrics remained stable across different decades; for example, the six decadal lines of the percent occurrence of zero flows at a non-seasonal stream, such as Beaver Creek near Rimrock, AZ (third row of plots on Figure 3), were all roughly overlapping each other. Visual inspection shows that there was no sequential shifting of the curves to either earlier or later months of when the curves transitioned from lowest to highest percent occurrence values and vice versa. For each month, the curves did not increase or decrease in such a way as to indicate intensification or abating of the flow metric. The overall general shape for each decadal curve was similar indicating that the seasonality of zero-flow events was roughly the same. For the largest 10% of flows at the same intermittent stream, the curves shift more frequently in the lateral and vertical directions than those for the zero-flow events. However, these lateral shifts were not occurring in any sequential order in time and appeared random. Similarly for each month, the percent occurrence values would decrease or increase over decadal time scales in a non-sequential manner. However, all the curves shared the same general shape indicating no substantial changes in the seasonality of the largest flows at this intermittent stream. The other types of intermittent streams show similar behaviour in their seasonality. In general, the stability of seasonality of the flow metrics at intermittent streams reflects the fact that decadal changes in precipitation seasonality have not occurred (Figures 3 and 4). The sensitivity of the analysis to the selected beginning and ending years for each

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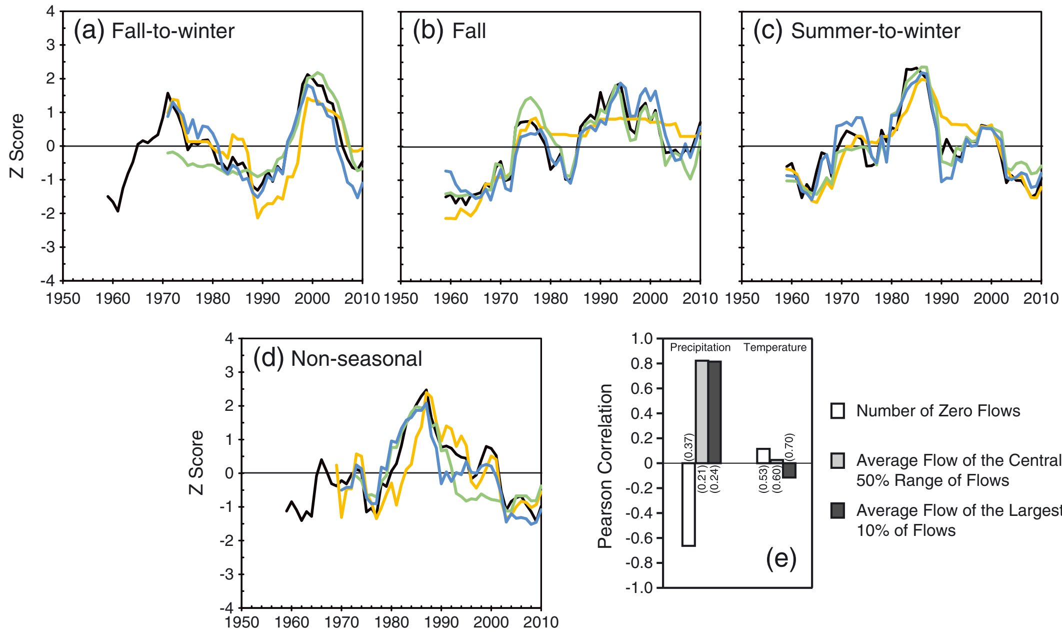

Figure 2. Plots of Z scores and average Pearson correlations for 10-year moving average of precipitation, number of zero-flow days, average flow of the central 50% range of flows and average flow of the largest 10% of flows. (a) Battle Creek near Keystone, SD (gauge 06404000: fall-to-winter intermittent stream), (b) Little Osage River at Fulton, KS (gauge 06917000: fall intermittent stream with highest precipitation in winter), (c) Tahquitz Creek near Palm Springs, CA (gauge 10258000: summer-to-winter intermittent stream with highest precipitation in winter), (d) Dry Beaver Creek near Rimrock, AZ (gauge 09505350: non-seasonal intermittent stream) and (e) average Pearson correlation values among Z scores for 10-year moving averages of precipitation, temperature and flow metrics over all streams. For Z score plots: Black lines are the precipitation scores, orange lines are the number of zero-flow days scores, green lines are the average flow of the central 50% range of flows scores and the blue lines are the average flow of the largest 10% of flows scores. The Z scores for the number of zero-flow days were multiplied by -1. For the average correlation values, the values in parentheses are the coefficient of variation. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

10-year block was evaluated, and it yielded similar results: The long-term seasonality was stable, and the percent occurrences shifted randomly.

The two-sample Kolmogorov–Smirnov tests indicated that the probability distributions for decadal periods were not significantly different from the probability distribution of the entire period of record for the majority of the long-term intermittent streams based on the p-values for the 342 comparisons at $\alpha = 0.05$ and 0.20 levels. Only 4% of comparisons across all long-term intermittent streams indicated differences that were significant at a 20% significance level, and only 2% of comparisons were significant at a 5% level. Based on visual inspection, the rejection of the null hypothesis occurred at locations and 10-year blocks that appeared to have no spatial or temporal patterns. Thus, the flow distributions across all long-term intermittent streams appear to be ‘sampled’ from the same long-term frequency distribution, even among wet and dry decades. This result also supports the initial assumption that the flow metrics calculated with short-term flow records were not statistically different from those based on longer records.

The long-term average percentage of zero-flow events and the average of the largest 10% of flows were both significantly correlated ($|\rho| >= 0.7$) with the duration of dry periods; the largest values for both types of flows were primarily located in the eastern portions of the study area (Figures 5a and 5d). The percentages of streams having significant correlations were 27% and 31% for zero-flow events and the average of the largest 10% of flows, respectively. The percentage of streams exhibiting significant correlations between the zero-flow events and average of the largest 10% of flows and duration of wet periods were 17% and 22%, respectively. The large negative correlation values for the zero-flow events, in general, clustered in the northern portions of the study area (North and South Dakota) and a few in the southwestern and most eastern parts of the study area (Figure 5b). The highest correlations among the average of the largest 10% of flows and duration of wet periods were mainly located in the Southwest (Arizona, California and New Mexico) and South Dakota (Figure 5e). There were significantly fewer streams whose zero-flow events and average of the largest 10% of the flows were correlated to the intensity of precipitation (Figures 5c and 5f). Only 6% and 9% of streams had a significant correlation for the zero-flow events and average of the largest 10% of flows, respectively.

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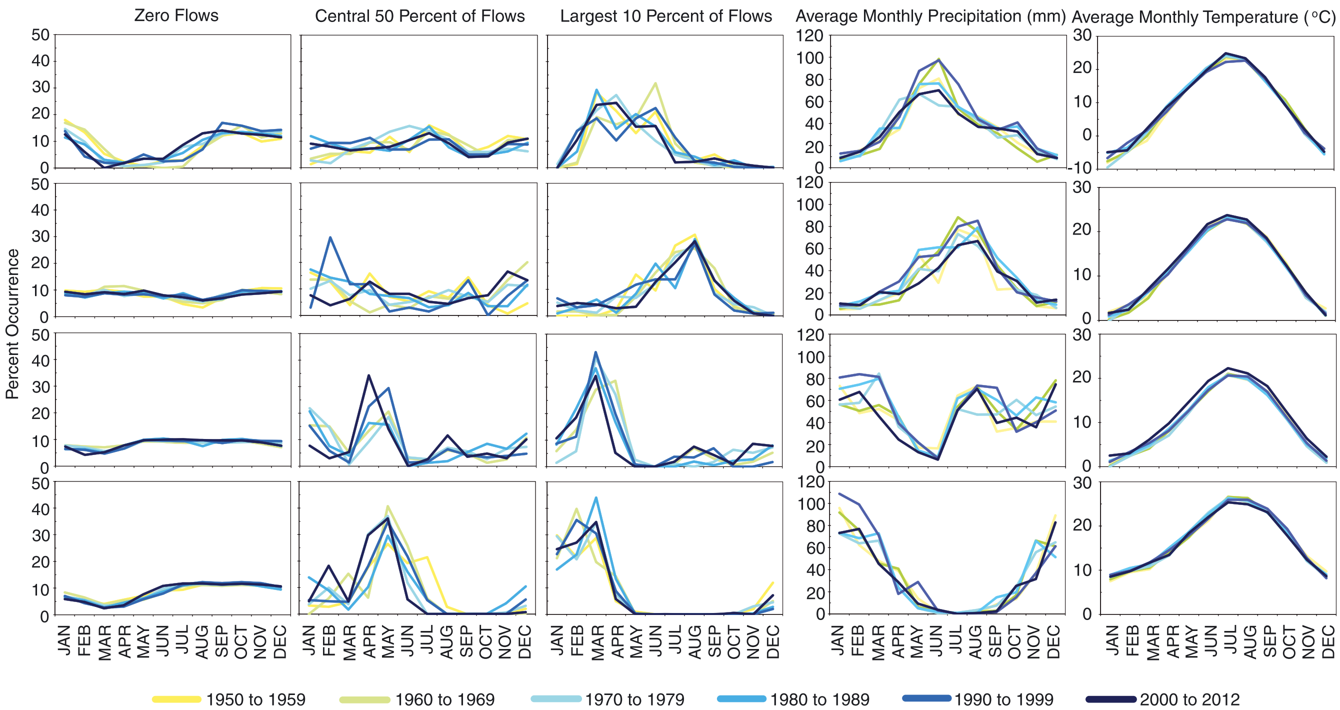

Figure 3. Percentage occurrence of zero flows, central 50% of flows, largest 10% of flows for each month, average monthly precipitation and temperature for fall-to-winter and non-seasonal intermittent streams. First row of plots for a fall-to-winter intermittent stream (gauge 06441500: Bad River near Fort Pierre, SD). Second row of plots for a non-seasonal stream with highest precipitation in spring/summer (gauge 07226500: Ute Creek near Logan, NM). Third row of plots for a non-seasonal stream with highest precipitation in fall and winter (gauge 09505350: Dry Beaver Creek near Rimrock, AZ). Fourth row of plots for a non-seasonal stream with highest precipitation in winter (gauge 11274500: Orestimba Creek near Newman, CA). This figure is available in colour online at wileyonlinelibrary.com/journal/rra

DISCUSSION

The five types of intermittent streams identified in this study (fall, fall-to-winter, non-seasonal, summer and summer-to-winter) were not completely distinct from each other in their spatial clustering; for example, a few summer-to-winter intermittent streams were geographically located in the cluster of fall-to-winter streams (Figure 1a). This indicates that there are other factors in addition to climate driving the seasonality of intermittent streams, such as local geology.

The large values of Pearson correlations suggest that changes in the number of zero-flow days, average of the central 50% range of flows and largest 10% of flows in the four types of intermittent streams are strongly associated with historical variations in climate; therefore, it is likely that any future changes in precipitation associated with global warming (e.g. Milly et al., 2005) would yield changes in all the dimensions of flow at these types of intermittent streams.

The flow frequency distributions at intermittent streams are stable and do not change from their long-term behaviour under differing decadal wet and dry cycles. This result is consistent with the findings by Botter *et al.* (2013) who found that the short and long-term behaviours of probability density functions of flows at ‘erratic’ streams—similar to our intermittent streams in this study—experienced little change.

The long-term seasonality of zero-flow events and the average of the largest 10% of flows were significantly correlated to both the duration of wet and dry periods. The intensity of precipitation, in contrast, had little impact on the seasonality of both flow metrics. For the relationships between these two flow metrics and the duration of dry periods in the eastern portions of the study area, the directions of these relationships make intuitive sense because the largest flows and zero-flow events should be impacted by the length of the dry periods (Figures 5a and 5d). However, the seasonality of the two flow metrics for the southwestern streams in this study was not well correlated to the duration of dry periods. A plausible explanation for this lack of dependence was that a simple Pearson correlation metric does not consider any lagged behaviour that was carried over from preceding months. As an example, the majority of these southwestern streams develop substantial water deficits that were carried over from preceding months due to high evapotranspiration and dry soil conditions during the spring-to-summer periods. As a result, precipitation events that occur after a prolonged period of these extreme dry periods have

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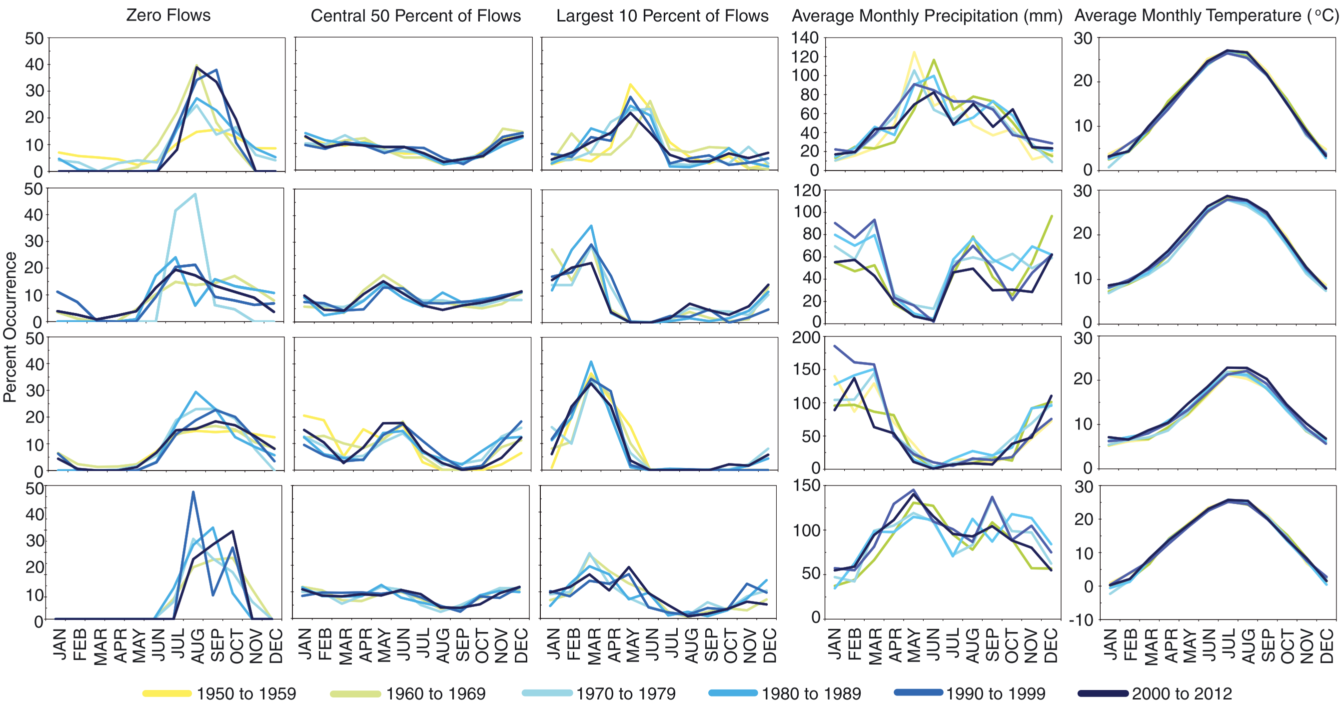

Figure 4. Percentage occurrence of zero flows, central 50% of flows, largest 10% of flows for each month, average monthly precipitation and temperature for summer-to-winter and fall intermittent streams. First row of plots for a summer-to-winter stream with highest precipitation in spring/summer (gauge 07301500: North Fork Red River near Carter, OK), second row of plots for a summer-to-winter stream with highest precipitation in fall and winter (gauge 09510200: Sycamore Creek near Fort Mcdowell, AZ), third row of plots for a summer-to-winter stream with highest precipitation in winter (gauge 11015000: Sweetwater River near Descanso, CA) and fourth row of plots for a fall stream with highest precipitation in spring/summer (gauge 06921200: Lindley Creek near Polk, MO). This figure is available in colour online at wileyonlinelibrary.com/journal/rra

had little impact on generating run-off (Figure 6c). The correlations between the average of the largest 10% of flows and the duration of wet periods in the southwest USA were not surprising because run-off production occurs primarily when there are sustained periods of precipitation when potential evapotranspiration effects were minimal (e.g. Figure 6c). For the streams in South Dakota, the largest duration of wet periods coincided with the time of snowmelt and precipitation events during spring (Figure 5f), so these events influence the seasonality of both the average of the largest 10% of flows and the zero-flow events (Figures 5b and 5e).

Fall-to-winter intermittent streams

Fall-to-winter intermittent streams—located in Kansas, western Minnesota, Nebraska, North Dakota and South Dakota (Figure 1a)—reflect the climatology of the region that includes low fall and winter precipitation (Figure 3) as well as storage of much cool-season precipitation in snow pack and ice. Unlike other intermittent stream types, the largest daily flows that occurred after the winter period (roughly from February to March) did not coincide with the period of maximum average precipitation. The high flows in this region were most likely generated by either occasional intense flood-generating warm storms or mid-cool-season melting of the snow pack that accumulated over the winter period (Figure 6a). Basins with thin snow pack in this region typically produce snowmelt that is not sufficient to sustain flows for long periods (Buttle et al., 2012) into summer and fall. For these basins, the combined effects of precipitation and snowmelt are insufficient to sustain baseflow throughout the year, and, therefore, streams cease to flow during the fall through winter period.

There have been several studies analysing temporal shifts in different portions of the flow regime due to climate variability at perennial streams with substantial snowmelt effects (e.g. Court, 1962; Hodgkins et al., 2003; Stewart et al., 2005; Déry et al., 2009, Hidalgo et al., 2009). Most of these studies have focused on basins with snow pack and/or ice where warming temperatures cause snowmelt and, thus, are altering the timing of the centre of flow volume. Confounding this effect, basins along the West Coast and southwestern USA experience occasional large winter storms where the precipitation is not always frozen resulting in large flow events occurring earlier than the snowmelt event. If the snowmelt in these streams occurs earlier and/or the timing of warm winter storms is changing, then the largest 10% of flows would exhibit a shift in timing. This shift in the timing of

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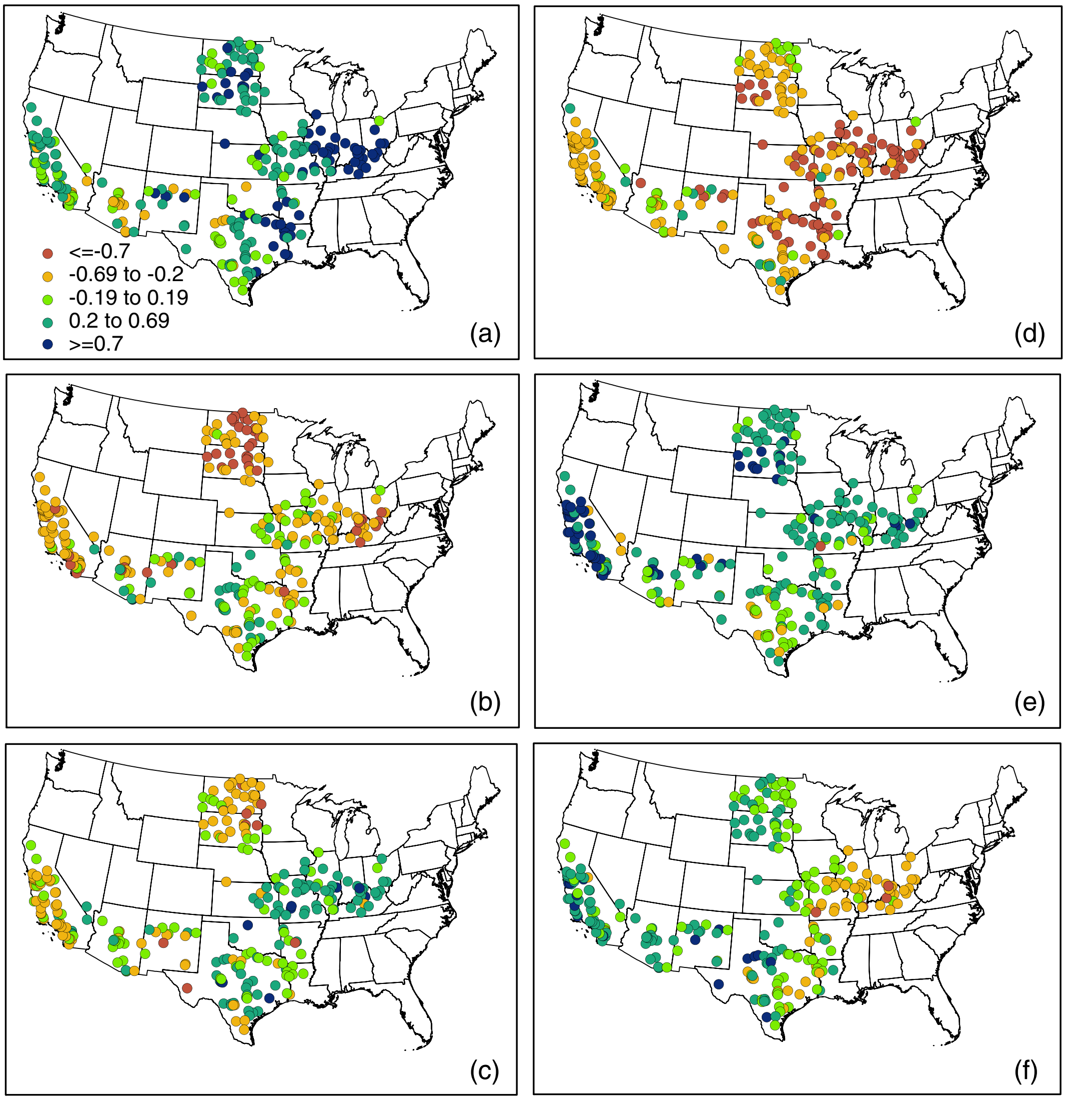

Figure 5. Pearson correlation values for zero-flow events and (a) duration of dry periods, (b) duration of wet periods and (c) daily precipitation intensity. Similarly, Pearson correlation values for the average of the largest 10% of flows and (d) duration of dry periods, (e) duration of wet periods and (f) daily precipitation intensity. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

the largest 10% of flows, however, was not observed in any fall-to-winter intermittent streams in our study. The discrepancy between our results and the aforementioned earlier work (e.g. Hodgkins et al., 2003; Hidalgo et al., 2009) may be due to regional differences in the study areas. Most prior work on snowmelt timing has been performed in New England and western USA. These areas typically have significant snowpack, unlike the intermittent sites we evaluated in Minnesota, Nebraska and the Dakotas.

Non-seasonal intermittent streams

For the non-seasonal streams with the highest precipitation in spring/summer and those with highest precipitation in winter, the largest flows coincided with the largest precipitation amounts (Figures 3, 6b and 6d). However, for the non-seasonal streams with the highest precipitation in fall and winter (Figure 3), the largest 10% flows were associated with the highest precipitation in winter and substantially fewer flow events during the fall. This effect could be due to the large water deficit caused by evapotranspiration during fall preceded by very dry soil conditions in the summer (Figure 6c), so the run-off generation is severely limited.

The non-seasonal streams in our study were distributed widely across mid to low latitude sites in semiarid to arid regions that experience differing and highly variable seasonal precipitation patterns reflected in the seasonal patterns of the largest 10% of flows and the central 50% range of flow

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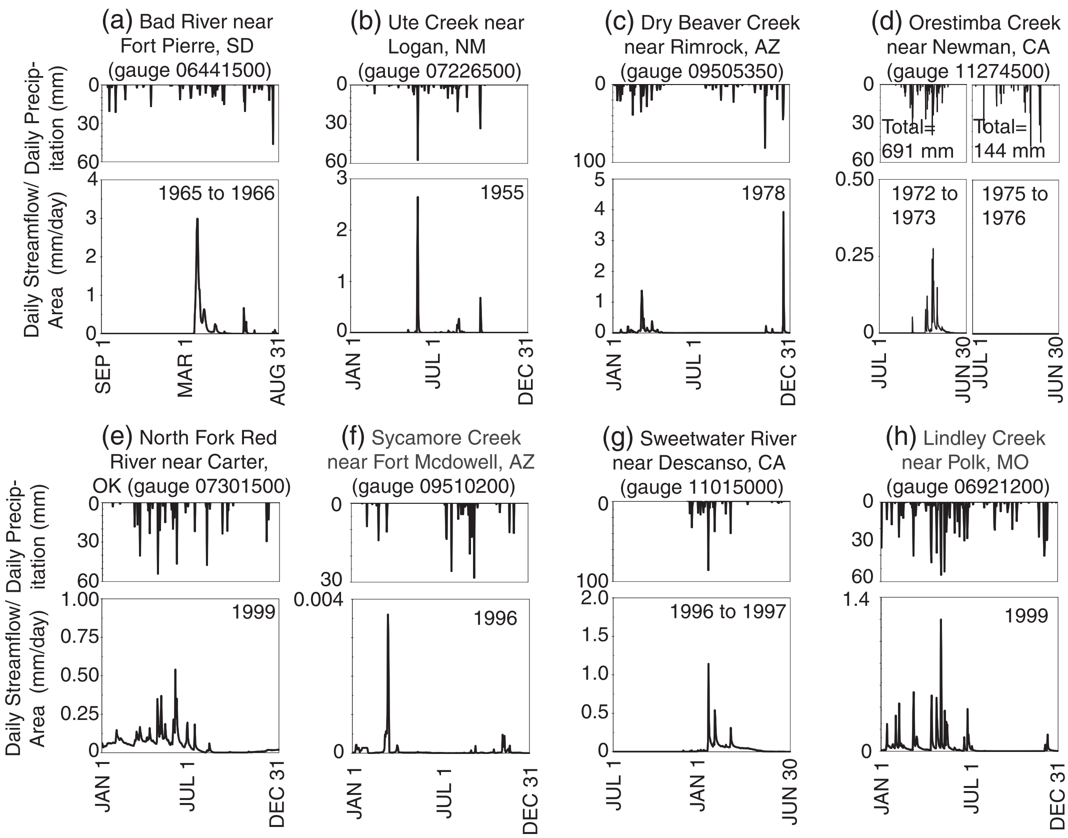

Figure 6. Daily precipitation and streamflow for (a) fall-to-winter intermittent stream, non-seasonal intermittent streams with highest precipitation in (b) spring/summer, (c) fall and winter and (d) winter, and summer-to-winter intermittent stream with highest precipitation in (e) spring/summer, (f) fall and winter, (g) winter and (h) fall intermittent stream with highest precipitation in spring/summer for selected 1-year periods.

values (Figure 1a); however, these climate patterns had little effect on the seasonal distribution of zero-flow events. Unlike the other groups of intermittent streams, non-seasonal intermittent streams with highest precipitation in spring/summer—located in Illinois, Kansas, Missouri, New Mexico, South Dakota and Texas—in general, had long-term (1950–2012) average monthly precipitation values consistently below the concurrent potential evapotranspiration values throughout the year (thereby maximizing actual evapotranspiration), which could explain why the number of zero-flow days was roughly invariant throughout the year. As a result of this water deficit, large (>20 mm) precipitation events are required to generate run-off in non-seasonal intermittent streams (Figure 6b). These intense events tend to be scattered among years and do not often correspond to season-long conditions, rather appearing mostly in brief bursts that leave ample opportunity for flows to fall to zero in between rains. For non-seasonal intermittent streams with highest precipitation in fall and winter—located in southeastern California and Arizona (Figures 3 and 6c)—the intra-annual precipitation is often unreliable in both winter and fall, so periods of no flow can develop in any portion of the year. In general, no run-off is produced by fall precipitation due to the high potential evapotranspiration and preceding dry period during summer. For non-seasonal intermittent streams with highest precipitation in winter—located in central to southern California—run-off is generated primarily during the winter period for most years in the flow record (Figure 6d, left plot); however, occasionally, the flows for an entire year may be zero despite the magnitude of precipitation events (Figure 6d, right plot). Comparison of the plots in Figure 6d shows that the precipitation is more frequent during years in which flow is generated, while the years that do not produce any flow have less frequent precipitation events and have an annual total precipitation amount of roughly 20% of those that occur during years with flow.

Summer-to-winter intermittent streams

The summer-to-winter intermittent streams include examples of three different precipitation patterns: highest precipitation during early spring/summer, highest precipitation in fall and winter and highest precipitation in winter. These types of streams were present throughout the study area

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(Figure1a). Despite the difference between the precipitation patterns for summer-to-winter intermittent streams with highest precipitation in spring/summer and those with highest precipitation in winter (Figure 4), the number of zero-flow events occurred during a similar period across these streams. This behaviour can be explained by the competing processes of precipitation, potential evapotranspiration and antecedent soil moisture. For the streams that had the highest precipitation during winter and early spring (typically associated with streams in southernmost California), the maximum potential evaporation coincides with periods of low precipitation from roughly June to October, which substantially inhibits run-off generation during this period (Figure 6g). Due to the combination of this dry period and the highly porous soils, run-off was generally produced only after sustained periods of precipitation and minimal evapotranspiration. As an example, Figure 6g shows that the first large (>30 mm) precipitation event following this dry period produces a very small amount of flow because there is a debt of 'missing' soil moisture that had to be filled before run-off was generated (e.g. Ralph et al. 2013). Similar-sized precipitation events that occur later in the year (February to April) produce substantially more flow due to the accumulation of soil moisture from preceding frequent precipitation events compared to storms that immediately follow a prolonged dry period. For the non-seasonal, fall-to-winter and summer-to-winter (highest precipitation occurring from early spring to summer) intermittent streams, there was a similar pattern of frequent precipitation events preceding larger events from the July to September period, but the flow values were generally small due to the large water deficits caused by evapotranspiration in excess of precipitation. For the streams that had the highest precipitation during early spring/summer, the period of lowest precipitation was from July to September, which is when we see the largest concentration of zero flows and lowest occurrences of the largest 10% of flow events (Figures 4 and 6e). For summer-to-winter intermittent streams with highest precipitation in fall and winter (Figures 4 and 6f), the period with minimal zero flows occurring is during the winter precipitation period with minimal potential evapotranspiration. Similar to the non-seasonal intermittent streams with highest precipitation in winter, an extended period of dry conditions begins in the spring through summer period; the erratic summer precipitation appeared to have a substantial impact on the long-term seasonality of the zero-flow events (Figures 3 and 4).

Fall intermittent streams

The fall intermittent streams fell primarily into two spatially grouped areas: California and areas generally east of the 95 ° meridian (Figure 1a). There were no long-term fall intermittent streams with highest precipitation in winter, so these types of streams are not discussed. For fall intermittent streams with highest precipitation in spring/summer—located in Arkansas, Illinois, Indiana, Kentucky, Louisiana, Missouri, Ohio and Texas—precipitation events during the fall tend to be smaller in magnitude and less frequent than those that occur throughout the rest of the year, and these events often fail to produce run-off due to the high potential evaporation (Figure 6h) similar to summer-to-winter intermittent streams with highest precipitation in spring/summer. Another similarity was that run-off was generated during periods of sustained and large precipitation events with minimal evapotranspiration (Figure 6h), which was during the late winter to early summer period.

In conclusion, the number of zero-flow days, average of the central 50% range of flows and largest 10% of flows at the four types of intermittent streams were found to be strongly correlated to historical variations in climate, so projected drying or wetting trends in precipitation due to climate change would impact all dimensions of the flow regime for intermittent streams. However, we did not observe any changes to the long-term seasonality pattern of zero-flow values, median and peak flows, which was due to the stable long-term seasonality in precipitation. In addition, observed changes to naturally intermittent streams would likely be amplified or diminished because of direct-human modifications to streams, such as dams, wastewater effluent and land-use changes.

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