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Alternative stable states and hydrological regime shifts in a large intermittent river

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Abstract

Non-perennial rivers and streams make up over half the global river network and are becoming more widespread. Transitions from perennial to non-perennial flow are a threshold-type change that can lead to alternative stable states in aquatic ecosystems, but it is unknown whether streamflow itself is stable in either wet (flowing) or dry (no-flow) conditions. Here, we investigated drivers and feedbacks associated with regime shifts between wet and dry conditions in an intermittent reach of the Arkansas River (USA) over the past 23 years. Multiple lines of evidence suggested that these regimes represent alternative stable states, including (a) significant jumps in discharge time series that were not accompanied by jumps in flow drivers such as precipitation and groundwater pumping; (b) a multi-modal state distribution with 92% of months experiencing no-flow conditions for <10% or >90% of days, despite unimodal distributions of precipitation and pumping; and (c) a hysteretic relationship between climate and flow state. Groundwater levels appear to be the primary control over the hydrological regime, as groundwater levels in the alluvial aquifer were higher than the stream stage during wet regimes and lower than the streambed during dry regimes. Groundwater level variation, in turn, was driven by processes occurring at both the regional scale (surface water inflows from upstream, groundwater pumping) and the reach scale (stream–aquifer exchange, diffuse recharge through the soil column). Historical regime shifts were associated with diverse pressures including network disconnection caused by upstream water use, increased flow stability potentially associated with reservoir operations, and anomalous wet and dry climate conditions. In sum, stabilizing feedbacks among upstream inflows, stream–aquifer interactions, climate, vegetation, and pumping appear to create alternative wet and dry stable states at this site. These stabilizing feedbacks suggest that widespread observed shifts from perennial to non-perennial flow will be difficult to reverse.

1. Introduction

Non-perennial streams—a category of hydrological features that do not flow year-round, including intermittent rivers and ephemeral streams (Busch *et al* 2020)—make up over half of the global river network (Messager *et al* 2021) and have become drier over the past half-century indicating an expansion of non-perennial flow (Zipper *et al* 2021). Streamflow and stream drying are driven by factors including meteorology, geology, land cover, and human actions (Zimmer *et al* 2020, Hammond *et al* 2021, Shanafield *et al* 2021), which interact over a range of spatial and temporal scales. Complex systems research has shown that cross-scale interactions can generate system configurations that are resilient to change due to stabilizing feedbacks that maintain the system in its current configuration (figure 1), often known as

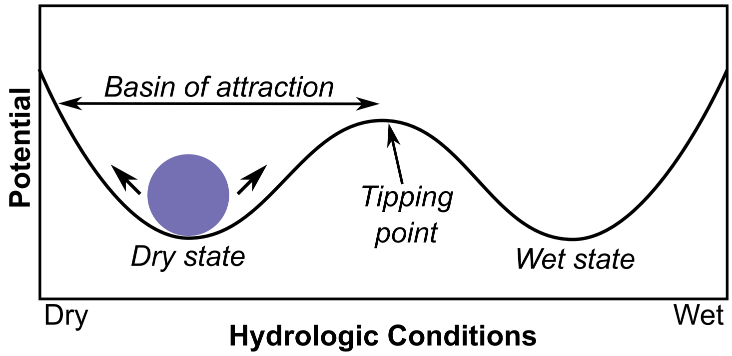

Figure 1. Stability landscape showing a hydrological system with alternative wet and dry stable states. In the ball's current position, hydrological feedbacks maintain the system within the dry basin of attraction unless a sufficiently large external forcing causes a regime shift by pushing the ball past the tipping point to the wet basin of attraction.

alternative stable states (Scheffer and Carpenter 2003, van Nes *et al* 2016). Regime shifts between stable states can occur when large perturbations in external forcings overwhelm these feedbacks and push the system across a tipping point (Rocha *et al* 2015, 2018).

Transitions from flow to no-flow are a threshold-type change, which are often (but not always) associated with alternative stable states (Dodds *et al* 2010, Capon *et al* 2015). Stream drying is a dominant determinant of aquatic ecosystem structure and function (Leigh *et al* 2016, Leigh and Datry 2017) and past work on alternative stable states in non-perennial streams has treated hydrology as an external abiotic driver of ecosystem processes, rather than an endogenous part of the ecohydrological system (i.e. Heffernan 2008, Bogan and Lytle 2011). However, both streamflow and groundwater can be subject to feedbacks that induce stability in different system states. In particular, theoretical modeling has demonstrated that interactions between surface and subsurface processes can lead to alternative hydrological stable states due to feedbacks between land surface and groundwater dynamics (Peterson *et al* 2009, Bense *et al* 2012, 2014, Peterson *et al* and Western 2014). However, no empirical studies have evaluated the evidence for flow and no-flow conditions as alternative stable states in non-perennial streams.

Our goal was to determine whether flowing and no-flow conditions represent alternative hydrological stable states and, if so, identify the feedbacks that create stability in both flowing and no-flow states and the pressures that induce regime shifts between states. To accomplish this, we characterized the historical hydrology of a large intermittent river, the Arkansas River near Larned, Kansas (USA) by investigating time series characteristics (jumps, multi-modality, and hysteresis) often associated with alternative stable states. We found evidence for stabilizing feedbacks between upstream surface water inflows, stream–aquifer exchange, climate, vegetation, and pumping. These feedbacks act over timescale from days to years and create alternative wet (flowing) and dry (no-flow) stable states. Regime shifts between stable states were associated with diverse human and climatic changes to the water cycle including surface water and groundwater use, extreme wet or dry climatic conditions, and reservoir construction.

2. Methods

2.1. Study site

The Kansas Geological Survey (KGS)'s Larned Research Site is on a 7^{th} order reach of the Arkansas River near Larned, KS (figure 2(a)), co-located with U.S. Geological Survey (USGS) stream gage 07141220 (figure 2(b)) and ~17 km downstream of the junction between the Pawnee and Arkansas Rivers. The river's sandy bed is channelized in a highly-conductive sand and gravel alluvial aquifer approximately 10 m in thickness and underlain by a low-permeability leaky clay layer separating the alluvial aquifer from the underlying High Plains aquifer (figure 2(c)) (Healey *et al* 2001, Butler *et al* 2004, 2007b, 2011). The Arkansas River was historically a gaining, perennial river with rare dry conditions in western Kansas, but surface and groundwater use for agriculture have caused long-term streamflow declines and drying of many rivers in western Kansas, and at the Larned Research Site the Arkansas River has periodically ceased to flow since at least 2002 (figure 2(a); Sophocleous and Perkins 1993, Whittemore 2002). The High Plains aquifer is heavily pumped for irrigation in the region, with over 1 million cubic meters of groundwater pumped annually within 2 km of the site (1990–2019 mean). The riparian floodplain at the site is dominated by phreatophytic cottonwood trees, which can induce water level fluctuations due to groundwater uptake when the water table is within the root zone (Loheide *et al* 2005, Butler *et al* 2007a).

2.2. Data

We compiled stream stage, stream discharge, groundwater level, groundwater pumping, and

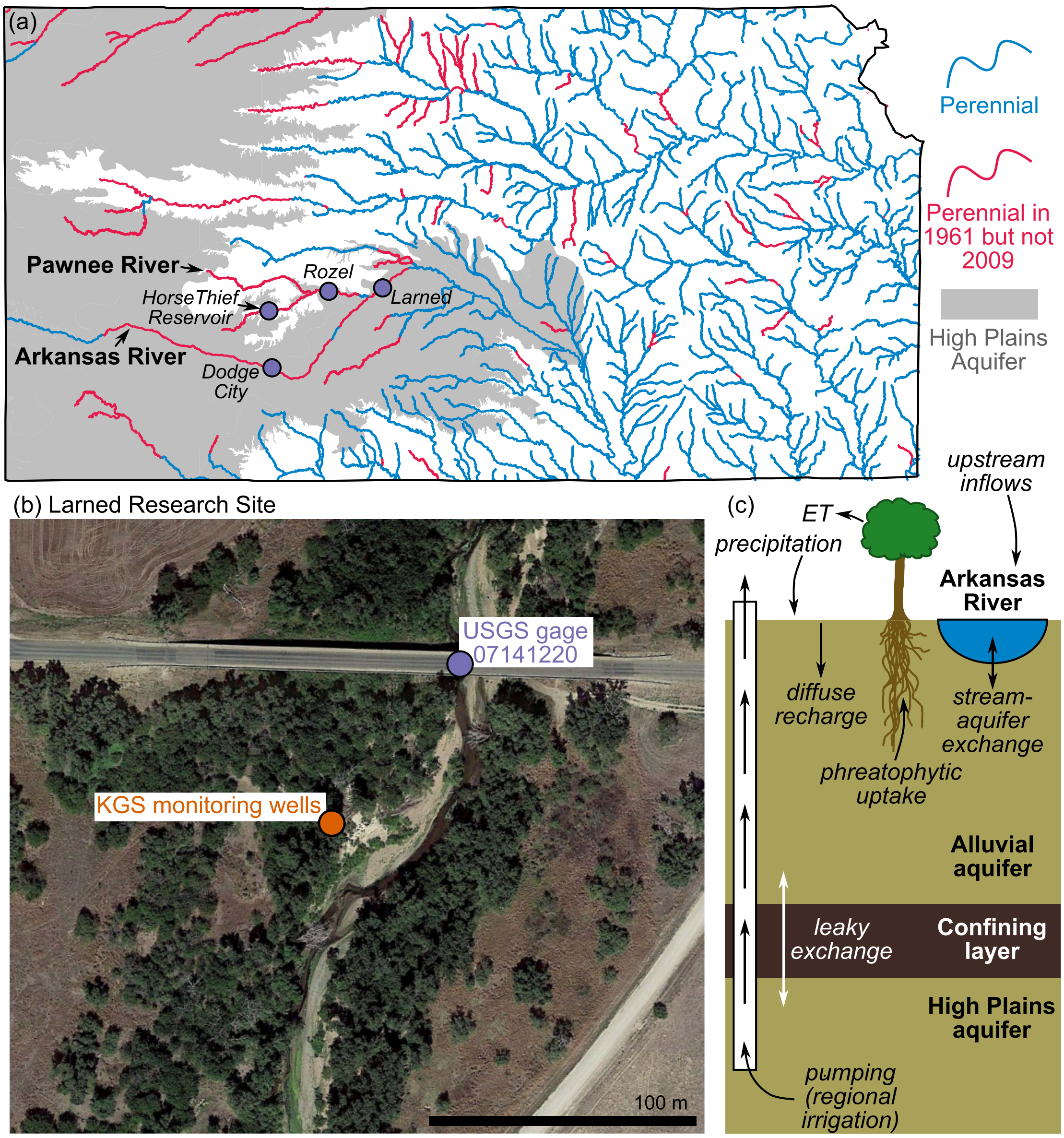

Figure 2. (a) Stream network in Kansas (USA), colored by flow status in 1961 and 2009. Hydrological features discussed in this manuscript are marked including the Arkansas and Pawnee Rivers, HorseThief Reservoir, and the gages on the Arkansas River at Dodge City, Pawnee River at Rozel, and Arkansas River near Larned. Data source: Kansas Surface Water Register. (b) Larned Research Site map including location of stream gage and nested monitoring wells used in this study. Flow is from south to north in the image. Imagery source: Google Earth. (c) Conceptual model of site (not to scale) showing primary hydrostratigraphic features (bolded text) and ecohydrological fluxes (italicized).

meteorological data for the Larned Research Site through the end of the 2021 water year. Daily mean stream stage and discharge have been monitored by the USGS since 1998 (gage 07141220), and daily mean groundwater levels have been monitored since 2003 from a nested set of wells installed by the KGS in the shallow alluvial, deep alluvial, and High Plains aquifers. We also collected streamflow data from upstream USGS gages including the Arkansas River at Dodge City (gage 07139500) and the Pawnee River at Rozel (gage 07141200). Irrigation in the vicinity of the Larned Research Site is sourced entirely from groundwater, so we extracted pumping data for the region from the KGS Water Information Management and Analysis System database. We found that a 4 km radius was most strongly correlated with annual High Plains aquifer water level change at the site, and used total pumping within 4 km of the study site as an indicator of groundwater use for subsequent analyses (see supplemental information for details).

We created a daily meteorological record of precipitation and temperature for both the site and the Pawnee River watershed for the period beginning 1 January 1904 from several nearby stations within the National Oceanographic and Atmospheric Administration Global Historical Climatology Network Daily database. To calculate atmospheric water demand, we calculated daily reference evapotranspiration (ETo) using the Hargreaves–Samani (Hargreaves and Samani 1985, McMahon *et al* 2013) approach as implemented in the 'Evapotranspiration' package for R (Guo *et al* 2022). We empirically corrected ETo through comparison with 10 years of American Society of Civil Engineers (ASCE) standardized grass ETo estimates from a nearby Kansas Mesonet station. We then used the monthly precipitation and ETo data to calculate the 12 month standardized precipitation evapotranspiration index (SPEI), an index of climatic water availability (Vicente-Serrano *et al* 2009, Zipper *et al* 2016, Peña-Gallardo *et al* 2019, Tramblay *et al* 2021), using the 'SPEI' R package (Begueria and Vicente-Serrano 2013). Negative and positive values of SPEI indicate drier- and wetting-than-average conditions, respectively.

Detailed information about the data sources and calculations are available in the supplemental information. All data and code used in this study are archived in Zipper *et al* (2022b).

2.3. Characterizing alternative stable states

We used a mixture of historical observational data, statistical tests, and hydrological time series models to evaluate the presence and drivers of stability at the Larned Research Site. To characterize historical stream intermittency, we extracted the duration of no-flow conditions as well as the date and season for the onset of no-flow for each time the USGS gaging station reported no-flow conditions.

While the presence of stable states can never be proven from observational data alone, we evaluated three lines of evidence that are often associated with alternative stable states in observational data (Scheffer and Carpenter 2003): (a) jumps in time series of the hydrological state variable in the absence of jumps in hydrological forcings, which we evaluated using the sequential t-test analysis of regime shifts (STARS) method (Rodionov 2004, Rodionov and Overland 2005); (b) a multi-modal distribution of the hydrological state in the absence of multi-modal distributions of driver variables, which we evaluated using an analysis of histograms; and (c) a hysteretic response of the hydrological system to drivers, which we evaluated by comparing the temporal dynamics of the hydrological state in response to hydrological forcings. For each of these three tests, we represented the hydrological system state using the percent of each month with no-flow conditions, and considered climate and groundwater pumping as potential forcing variables. We used monthly resolution to minimize the impacts of short-term precipitation-driven rewetting events.

To understand ecohydrological feedbacks that could contribute to stability, we investigated regional-scale relationships between flow at the Larned Research Site and discharge at upstream stream gages, and reach-scale relationships between water levels in the river, alluvial aquifer, and High Plains aquifer. To support our interpretations of these hydrological data, we also developed a time series model using a transfer function noise approach (Von Asmuth *et al* 2008, Bakker and Schaars 2019, Collenteur *et al* 2019). This model estimated the degree to which historic variation in alluvial aquifer water levels could be attributed to three drivers: (a) climate-driven diffuse recharge through the soil column, represented in the model using a simple soil water budget model driven by precipitation and ETo (Collenteur *et al* 2021); (b) stream–aquifer exchange, represented via a linear response to stream stage variation; and (c) groundwater pumping, represented via the Hantush and Jacob (1955) response to pumping. This model does not simulate the potential existence of multiple stable states because it does not include interactions among these factors, but provides an indication of the relative importance of each of these drivers on water levels in the alluvial aquifer, and the time scale over which each of them influences alluvial aquifer water levels. Additional model details are in the supplemental information.

3. Results and discussion

3.1. Historical stream intermittency

The Arkansas River near Larned dried for the first time during our study period on 18 April 2002 (figure 3(a)). During the period of record, there have been a total of 28 dry events, ranging in length from one to 789 consecutive days. While most dry events were relatively short, the majority of historical no-flow conditions were concentrated in relatively few, long-duration dry events (figure 3(b)) that were occasionally interrupted by ephemeral, short-duration flow. For example, from 18 June 2011 to 7 May 2015 the river was dry for a total of 1404 out of 1422 days (98.7% of the time). While dry events can start in any season, the largest number and longest average duration of dry events began during the summer (figure 3(c)).

3.2. Evidence for alternative stable states

All three lines of evidence we evaluated suggested the existence of alternative hydrological stable states at the Larned Research Site. First, there were abrupt jumps from persistent flow (0% no-flow days in a month) to persistent no-flow (100% no-flow days in a month) conditions, and vice versa, throughout the period of record (figure 4(a)). The STARS algorithm identified a series of five alternating wet and dry regimes with significant regime shifts occurring in April 2002 (wet to dry), January 2007 (dry to wet), June 2011 (wet to dry), and April 2016 (dry to wet). The final wet regime included some shorter-duration transitions between flowing and no-flow conditions, and could perhaps be considered a more extended transitional period between dry and wet that spans from April 2016 to July 2018 (Popescu *et al* 2022). None of the jumps in hydrological time series were accompanied by jumps in either precipitation (figure 4(b)) or pumping (figure 4(c)), with the possible exception

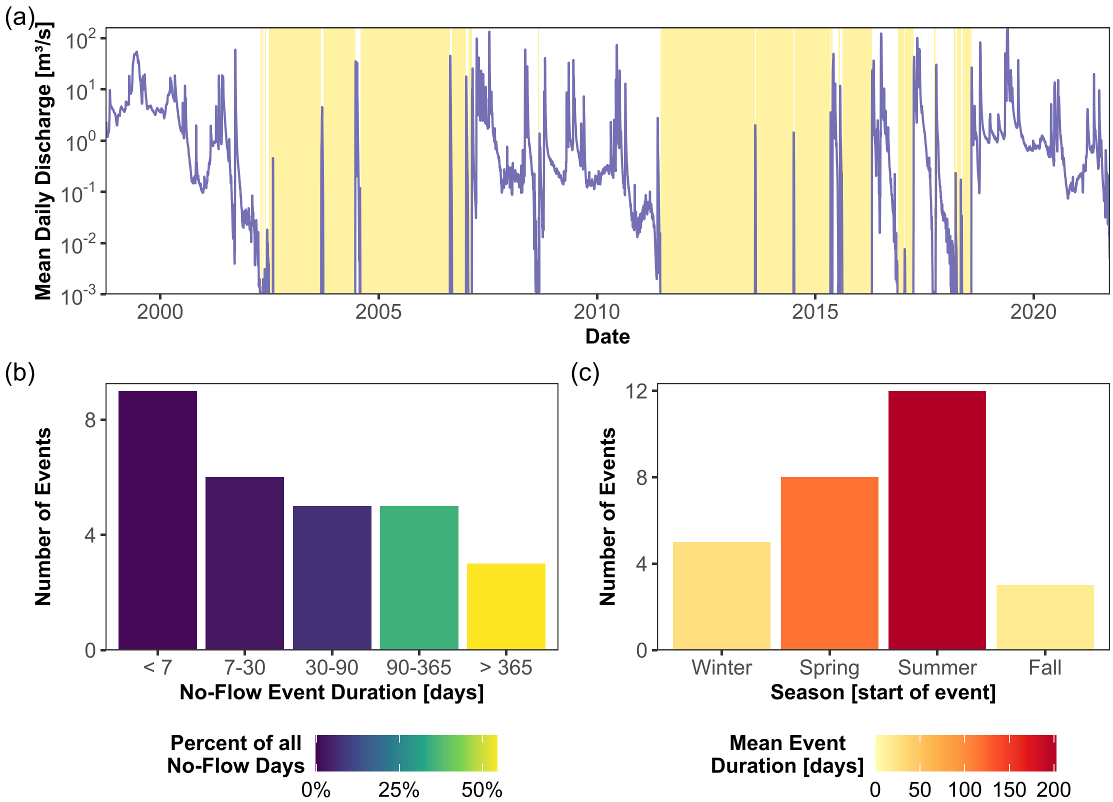

Figure 3. Characteristics of historical stream intermittency. (a) Daily discharge hydrograph. Yellow shading indicates periods of no-flow. (b) Number of no-flow events grouped by the duration of the event. Colors indicate the percentage of the total number of no-flow days falling in each no-flow duration bin. (c) Seasonal distribution of the onset of no-flow conditions, colored by the mean no-flow duration for an event beginning in that season. Winter = December–February, Spring = March–May, Summer = June–August, Fall = September–November.

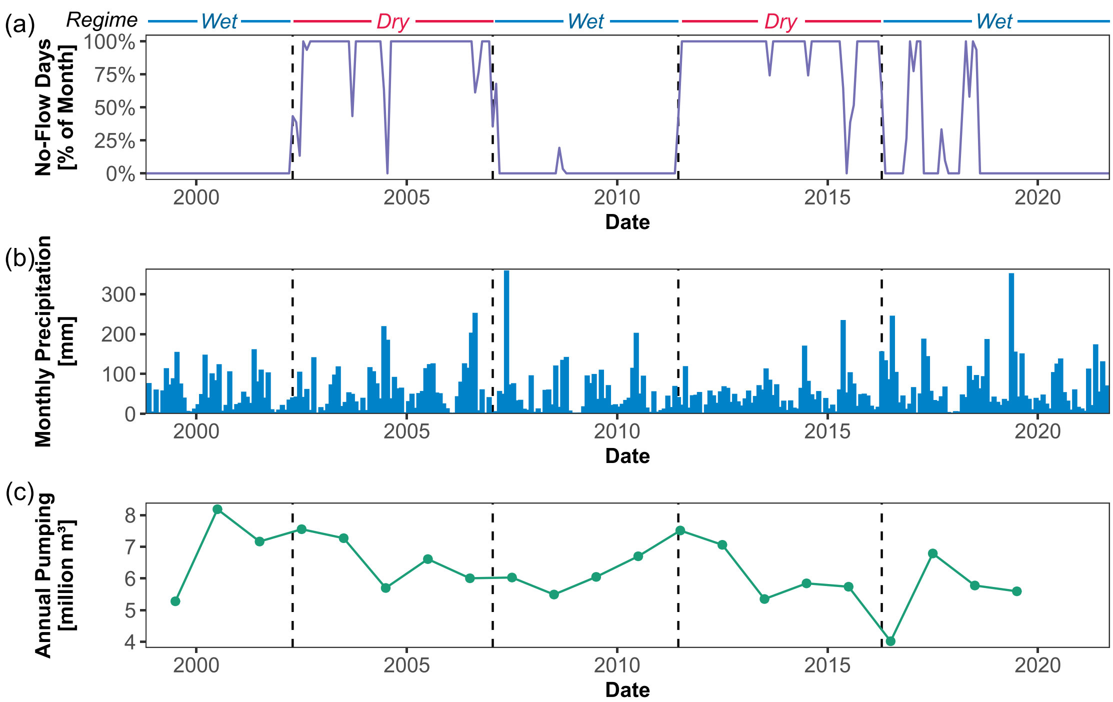

Figure 4. There were significant jumps in the time series of (a) the number of no-flow days as a percentage of each month, but no corresponding jumps in either (b) monthly precipitation or (c) annual pumping within 4 km of the study site. Dashed lines indicate regime shifts identified using STARS analysis, which are classified along the top.

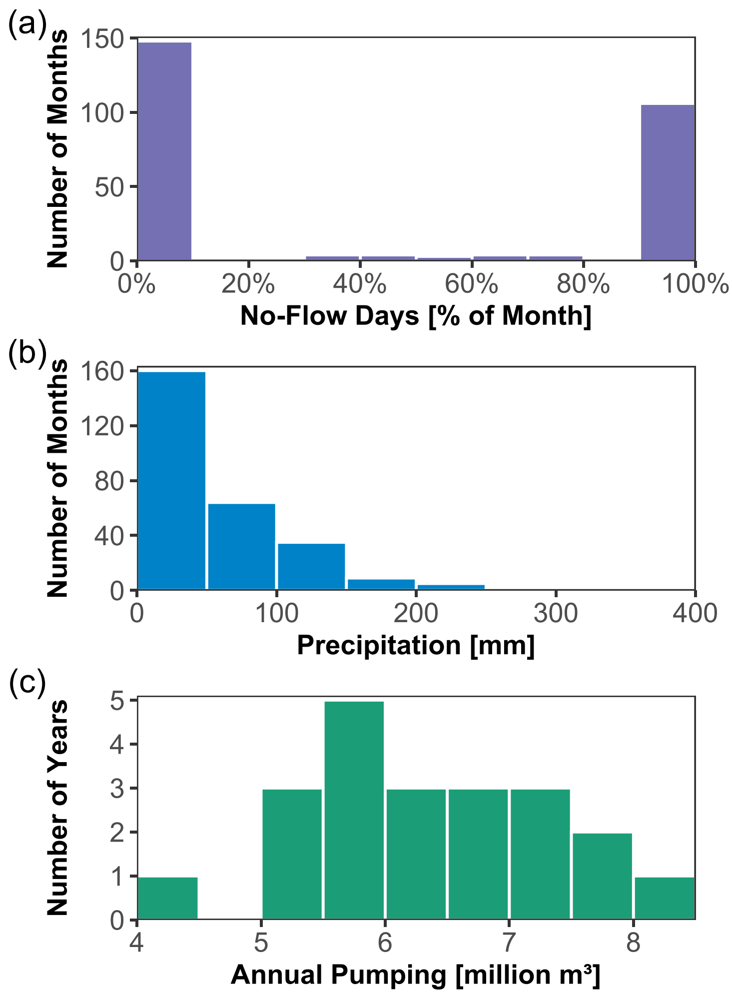

Figure 5. Histograms showing the distribution of (a) monthly percent of no-flow days, (b) monthly precipitation, and (c) annual pumping within 4 km of the study site.

of the 2007 dry-to-wet transition that occurred during a particularly wet spring both at the site and in the Pawnee River watershed (figures 4(b) and S2). While there were no jumps in pumping time series, there was evidence for lagged impacts of pumping on streamflow. For example, the 2002 wet-to-dry regime shift occurred in the midst of a four-year stretch of higher-than-average pumping and the 2011 wet-to-dry regime shift occurred after four years of steadily increasing pumping, while the 2016 dry-to-wet regime shift is coincident with the lowest pumping on record (figure 4(c)). The jumps in hydrology suggest that there has been a highly nonlinear and potentially lagged flow response to changes in drivers.

Second, the Arkansas River near Larned had a strongly bimodal hydrological state distribution, but unimodal distributions of both precipitation and pumping. Of the 276 months during our period of analysis, 254 months (92%) had no-flow conditions either <10% of days (148 months) or >90% of days (106 months) (figure 5(a)). Monthly precipitation exhibited a unimodal right-skewed distribution (figure 5(b)), reflecting the seasonal pattern of precipitation in the region (figure 4(b); Compare *et al* 2021), and annual pumping in the region exhibited a unimodal normal distribution (figure 5(c)). Since monthly pumping data are not available and stabilizing hydrological feedbacks can vary as a function of timescale (Peterson and Western 2014), we also evaluated modality with no-flow days and precipitation aggregated to an annual scale to match pumping data. At the annual scale, no-flow days still had a strong bimodal distribution and precipitation and pumping both had unimodal distributions (figure S3). Thus, the mismatch between the state distributions of the hydrological system (bimodal) and potential driver variables (unimodal) in both monthly and annual data suggested the existence of alternative stable states.

Third, stream intermittency at the Arkansas River near Larned responded to climate in a hysteretic manner. The relationship between no-flow days and SPEI had a clear clockwise loop as the hydrological system shifted between wet and dry states (figure 6). We divided the total period of record into two wet-dry-wet cycles based on the STARS algorithm so that the progression of time through different hydrologic states was evident. In each cycle, we found that a substantial dry climate anomaly (SPEI < -1) was

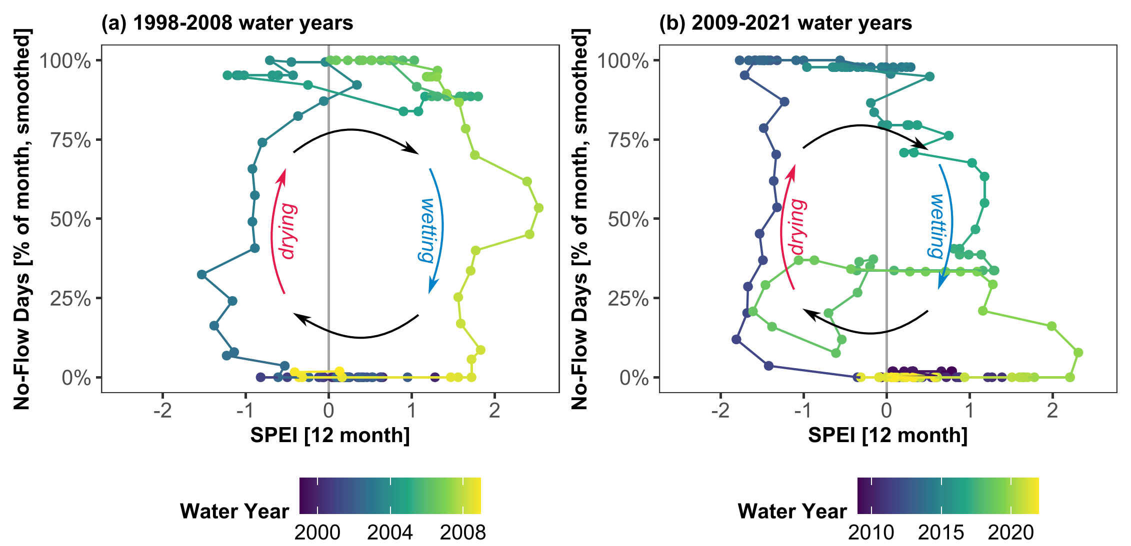

Figure 6. Hysteretic response of stream intermittency (percent of each month with no-flow conditions) to climate (12 month standardized precipitation evapotranspiration index, SPEI) for (a) 1998–2008 and (b) 2009–2021 water years. In each wet-dry-wet cycle, the system progressed through a clockwise hysteresis loop. Negative SPEI indicates dry climatic conditions and positive SPEI indicates wet climatic conditions. Monthly no-flow days were smoothed using a 12 month moving average to match the timescale of the SPEI.

necessary for the river to dry. For flow to resume, the climate had to become wetter than average (SPEI > 0). In the second wet-dry-wet cycle (2009–2021), there was a brief negative climatic excursion during the re-wetting phase which led to a nested counterclockwise hysteresis loop (figure 5(b)). This excursion was the potential transitional period between 2016 and 2018 in which the river shifted between wet and dry conditions, seen in figure 4(a) and described earlier in this section.

Taken together, these three lines of evidence strongly suggest the existence of alternative hydrological stable states for the Arkansas River near Larned. Both jumps in time series (Rodionov and Overland 2005, Stirnimann *et al* 2019) and multi-modal state distributions are common indicators of alternative stable states (Kosten *et al* 2012, Buschke *et al* 2013). The historical hydrological time series clearly shows both jumps (figure 4) and multi-modality (figure 5), while these characteristics are not present in either climate or pumping time series, indicating a nonlinear response of the hydrological system to potential drivers. However, neither time series jumps nor multi-modality are definitive proof of stability because the bimodality may be driven by threshold-type responses to drivers (Scheffer and Carpenter 2003). The hysteretic response of streamflow to climate (figure 6) provides an additional indicator of stability by demonstrating that restoring the system to the climatic conditions that existed before a regime shift was insufficient to reverse the shift and revert to the previous state (Hansen *et al* 2013). In summary, all the empirical lines of evidence we evaluated indicated that the hydrological system at the Larned Research Site is characterized by alternative wet and dry stable states.

3.3. Regime shift drivers

3.3.1. Changing surface water inflows from upstream

While our analysis focuses on the Larned Research Site, this reach is near the downstream end of hundreds of kilometers of the Arkansas River that have transitioned from perennial to non-perennial flow over the past 70 years due to upstream surface water and groundwater use (figure 2(a); Whittemore *et al* 2006, Koehn *et al* 2019, 2020, Zimmer *et al* 2020). Since 2001, there have only been two days of flow at the closest upstream gage along the Arkansas River (Dodge City; ∼115 km upstream), though surface water inflows from Colorado into Kansas (∼325 km upstream) have remained relatively stable over the period of record due to an interstate water compact (figure S4). The first wet-to-dry shift, in April 2002, occurred shortly after upstream flow ceased (figure 7), and this regime shift appears to have been driven by upstream surface water and groundwater use that caused the Larned Research Site's disconnection from the water supply from the headwaters in Colorado.

After the Arkansas River near Larned was disconnected from stable surface water inflows from Colorado, the Pawnee River became the primary contributing area to the gage at Larned, and both dry-to-wet regime shifts are associated with high flow events in the Pawnee River (figure 7). While the Pawnee River historically flowed only ephemerally in response to precipitation events (less than 30% of days between October 1998 and May 2018), the Pawnee River at Rozel flowed 93.8% of days from June 2018 through September 2021. This increase in flow persistence on the Pawnee River coincided with flowing conditions at the Larned Research Site and may be driven by the construction of the HorseThief Reservoir in the

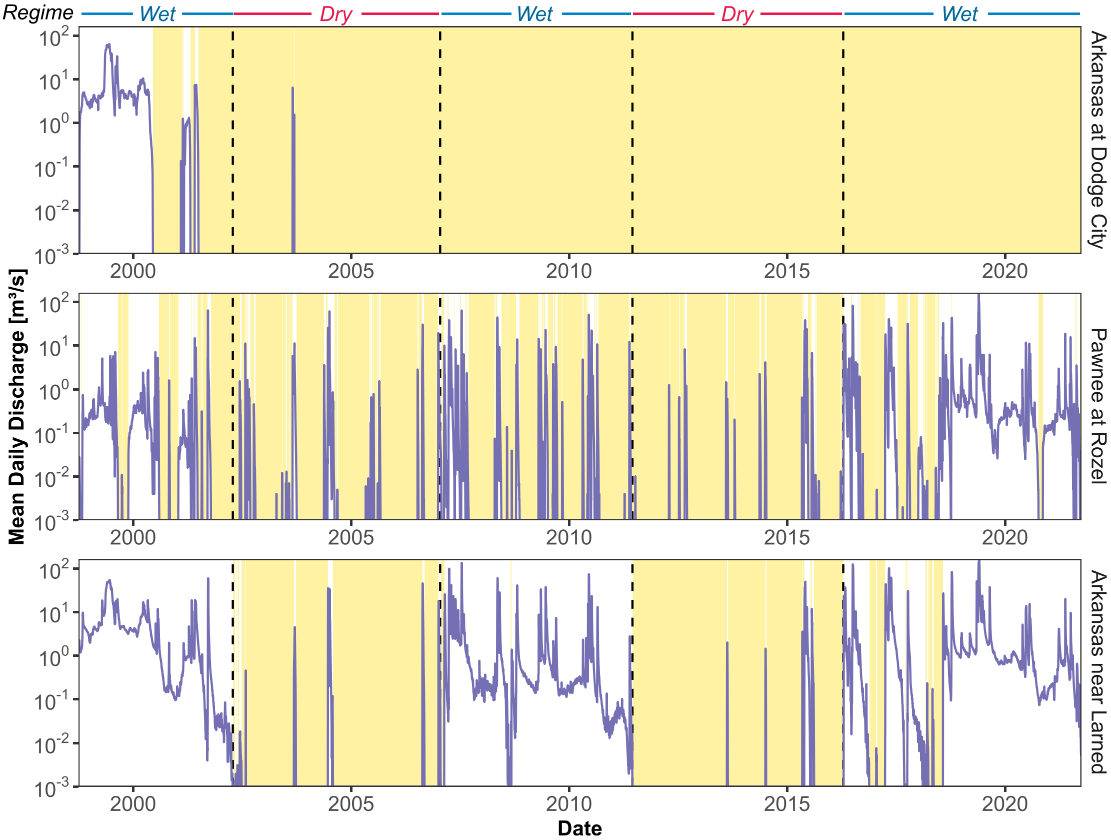

Figure 7. Daily streamflow at three gages: the Arkansas River at Dodge City, which is the closest upstream gage along the Arkansas River; the Pawnee River at Rozel, which is the closest upstream gage in the Pawnee River that joins with the Arkansas River just upstream of Larned; and the Arkansas River near Larned, which is the focus of our study. In each panel, yellow shading indicates no-flow conditions at that site. Dashed lines with blue and red notation at the top of the panel indicate wet and dry regimes, respectively, for the Arkansas River near Larned identified by the STARS analysis in .figure 4.

Pawnee River watershed (figure 2), which was completed in September 2009 and filled to capacity in July 2016 (Kansas Department of Agriculture 2016). The HorseThief Reservoir has maintained streamflow by providing outflows exceeding inflows during some dry periods since 2016, though outflows were substantially lower than inflows during parts of 2020 and 2021 (figure S5). However, the influence of the reservoir on downstream flow persistence is challenging to isolate because precipitation has been higher than average since 2016 (figures 4 and S2). Overall, this suggests that the Pawnee River watershed emerged as the key control over the hydrological state at the Larned Research Site after the disconnection from the upstream Arkansas River watershed, with a combination of wet climatic conditions and outflows from the HorseThief Reservoir potentially contributing to the stability of the current wet regime.

3.3.2. Local ecohydrological feedbacks

Changing upstream inflows interacted with local-scale ecohydrological processes to determine the flow regime at the Larned Research Site. Regime shifts in surface water flow were accompanied by changes in groundwater levels that induce a reversal of the hydraulic gradient at the site (figure 8). There was a downward hydraulic gradient during the dry regimes, with water levels in the semi-confined High Plains aquifer lower than water levels in the unconfined alluvial aquifer. There was rarely streamflow during dry regimes, but when there was, water levels in the river typically peaked at a higher value than the alluvial aquifer, indicating transmission losses and recharge from the stream into the alluvial aquifer (Shanafield and Cook 2014, Villeneuve *et al* 2015, Koehn *et al* 2020). There was also a clear seasonal pumping signal in the High Plains aquifer at the site, characterized by reductions in water level during the summer and recovery during the winter (Butler *et al* 2021). The declines in alluvial aquifer water levels during pumping in dry regimes (i.e. summer 2012) suggest that pumping in the High Plains aquifer induces downward flow through the leaky confining layer (figure 2(c)), leading to a lagged and dampened decline in alluvial aquifer water levels, which is consistent with past work at the site (Butler *et al* 2007b, 2011). In contrast, during wet regimes, there was a persistent upward gradient with the highest water levels in the High Plains aquifer, intermediate water levels in the alluvial aquifer, and lowest water levels in the river. This gradient allowed streamflow to persist through periods with minimal precipitation within

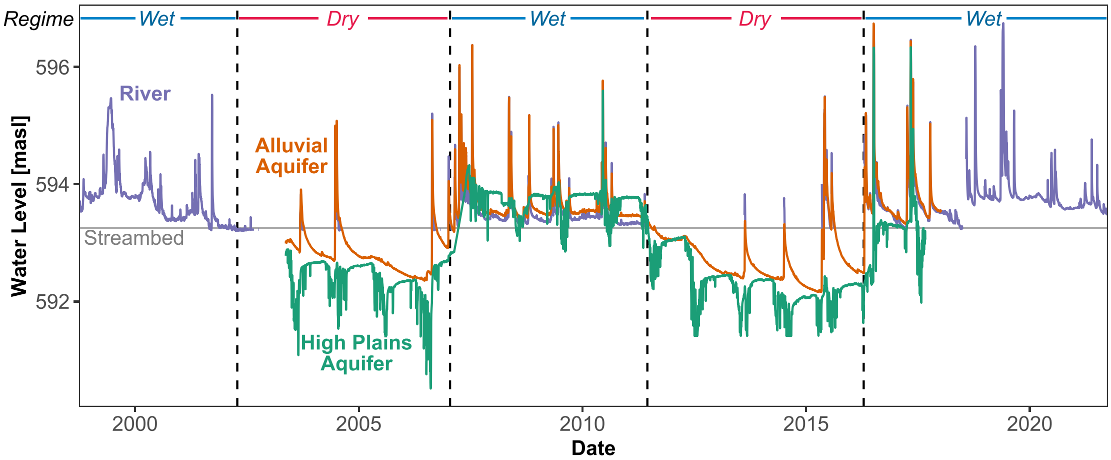

Figure 8. Time series of water levels in the Arkansas River, alluvial aquifer, and High Plains aquifer. Gaps in the river stage data correspond to the periods when the river was dry. Blue and red notation at the top of the panel indicate wet and dry regimes, respectively, identified by the STARS analysis in figure 4.

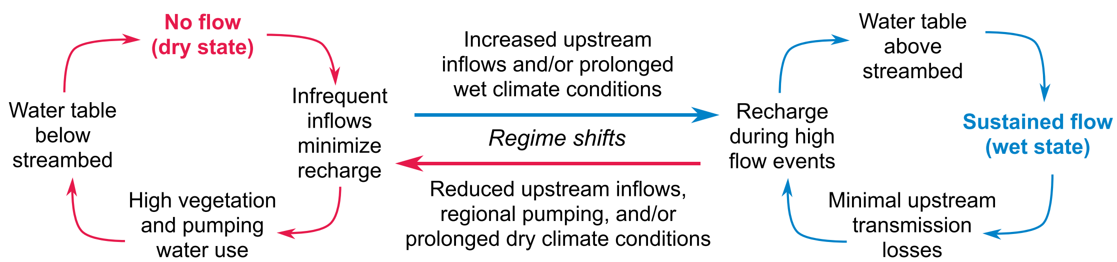

Figure 9. Conceptual model of stabilizing feedbacks within dry and wet states and drivers of regime shifts at the Larned Research Site.

the wet regimes. The results from our time series model support this interpretation, showing that the alluvial aquifer water levels responded immediately to changes in stream stage, while the response to diffuse recharge through the soil column was primarily on seasonal to annual timescales and reductions in alluvial aquifer water levels due to pumping were lagged over multiple years (figure S7).

3.4. Interactions and complexity across scales

We propose that cross-scale interactions between regional processes (surface water inflows from upstream, groundwater pumping) and local ecohydrological feedbacks (stream–aquifer exchange, diffuse recharge through the soil column) govern streamflow and can trigger regime shifts at this site (figure 9). The two primary ecohydrological feedbacks in the system are the balance between precipitation and plant water use in the riparian corridor, which drives the amount of diffuse recharge through the soil column (Collenteur *et al* 2021), and groundwater pumping for agricultural use, which is sensitive to precipitation at the regional scale and depletes streamflow by lowering groundwater levels locally and reducing inflows from upstream (Whittemore *et al* 2016, Zipper *et al* 2022a). These cross-scale interactions suggest that the alternative stable states we observed here are symptomatic of stressors related to human activity and climate over much of the Arkansas River basin, and this site is a reflection of the broad-scale shift from perennial to non-perennial streams in western Kansas (figure 2(a)), the Great Plains (Perkin *et al* 2017), and worldwide (Sauquet *et al* 2021, Tramblay *et al* 2021, Zipper *et al* 2021).

Dry-to-wet regime shifts in 2007 and 2016 were associated with wet climatic conditions and high inflows from the Pawnee River watershed, which recharged the alluvial aquifer through both stream–aquifer exchange and diffuse recharge, creating gaining conditions that sustained flow at the site (figure 8). By contrast, wet-to-dry regime shifts in 2002 and 2011 occurred when there was a reduction in upstream inflows to the site and dry climate conditions or pumping caused water levels in the alluvial aquifer to fall below the streambed for a sustained period of time. The importance of upstream inflows was particularly evident in 2002, when upstream water use dried the central portion of the Arkansas River and cut the Larned Research Site off from a consistent supply of water (figure 7). The 2011 wet-to-dry regime shift appeared more driven by local factors and drying occurred when pumping caused groundwater levels in the High Plains aquifer and, indirectly, the alluvial aquifer to fall below the streambed elevation, indicating the role of pumping in the High Plains aquifer in causing stream drying (figure 8). Both dry regimes began when there was a dry climate anomaly (figure 6) and dry periods began most frequently in the summer pumping season (figure 3). Given the strong negative correlation between pumping and precipitation at this site (Compare *et al* 2021) and across the region (Whittemore *et al* 2016, Butler *et al* 2018), drought and pumping appear to be compounding and interacting disturbances that can combine to induce a wet-to-dry regime shift.

These cross-scale interactions suggest that the local ecohydrological system can maintain stability in either wet or dry states, and that the state of the system is ultimately dependent on regional factors (upstream inflows, regional groundwater pumping, and climate conditions) that exert pressure on the local system (figure 9). This builds on past work on complex ecohydrological systems, which has found that local feedbacks can induce stability in systems ranging from drylands (Mayor *et al* 2019) to boreal forests (Johnstone *et al* 2010). While our work focused on a single stream reach, drought-induced transitions to alternative hydrological stable states have been suggested to occur across broad scales, for example the persistent reduction in streamflow following the Millennium Drought in Australia (Peterson *et al* 2021), and appear linked to groundwater declines in some streams (Kinal and Stoneman 2012). Since groundwater can have an outsized importance for sustaining aquatic ecosystems (Burns *et al* 2017, Larsen and Woelfle-Erskine 2018) and has been identified as a key feedback in previous studies of hydrological regime shifts and stable states (Peterson *et al* 2009, Bense *et al* 2012, Park and Rao 2014), this suggests that interlinked groundwater-surface water systems may be control points of stability in landscapes with potentially important ramifications for ecosystem structure and function.

3.5. Implications for land and water management

When considered through the lens of the 23 year period of record for this site, our analysis suggested there are distinct wet and dry regimes. However, from a multi-generational perspective the wet and dry regimes we identified here may represent a single transitional period from a historical wet regime to a future dry regime. The future state of the Arkansas River likely depends on both local and global human activities related to water use, water and land management, and climate change, which are already in tension. In the case of the Arkansas River near Larned, it appears that upstream water use triggered the first shift to a dry regime, and wet conditions and reservoir operations in the Pawnee River watershed may have pushed the system back to a wet regime (figure 7).

The management actions that triggered these hydrologic regime shifts were implemented to maximize specific upstream ecosystem services: agricultural production in the case of upstream water use, flood control and recreation in the case of the HorseThief Reservoir. However, non-perennial streams provide diverse ecosystem services, which can vary nonlinearly in response to water availability (Qiu *et al* 2018, 2019) and differ between flowing and no-flow states (Kaletová *et al* 2019, Stubbington *et al* 2020), and therefore the management for upstream ecosystem services inadvertently led to a shift in the provision of ecosystem services at the downstream Larned Research Site. These interlinkages suggest that effective management requires integrating synergies and tradeoffs among ecosystem services through space and time, for example by balancing the services gained from upstream water use against potential losses in downstream flow-driven services such as water supply and water quality in the Arkansas River near Larned. Since regime shifts are characterized by nonlinear change and likely to be difficult to reverse, avoiding regime shifts may have outsize benefits but effective management requires detailed characterization of stabilizing feedbacks and potential cross-scale interactions that may trigger undesired regime shifts.

4. Conclusions

We evaluated multiple lines of evidence, all of which suggest that dry (no-flow) and wet (flowing) conditions represent alternative stable states for the intermittent Arkansas River. Over the past 23 years, there have been four regime shifts at the site which appear to have been driven by changes in surface water inflows from upstream, groundwater use near the site, climate in upstream areas, and ecohydrological feedbacks occurring at the site. Regime shifts can be triggered by human actions, such as the disconnection of the site from headwaters due to stream drying caused by upstream water use, and natural phenomena such as anomalously wet or dry climatic conditions. Ultimately, groundwater levels in the alluvial aquifer at the site are the primary control over the hydrological regime at the stream reach scale. Wet-to-dry regime shifts occurred when the water levels in the alluvial aquifer declined below the streambed, inducing losing conditions from the stream to the aquifer, while dry-to-wet regime shifts occurred when wetter-than-normal meteorological conditions upstream led to substantial surface water inflows, recharge from the stream into the aquifer, and diffuse groundwater recharge through the soil column that caused gaining stream conditions. Future research is needed to determine the degree to which these processes are generalizable to other settings, but the existence of alternative wet and dry stable states in a large intermittent river suggests that the observed worldwide loss of perennial streams may be challenging to reverse.

Data availability statement

Data and code are archived and available in Zipper *et al* (2022b).

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