

Irrigation intensification impacts sustainability of streamflow in the Western United States

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Quantifying the interconnected impacts of climate change and irrigation on surface water flows is critical for the proactive management of our water resources and the ecosystem services they provide. Changes in streamflow across the Western U.S. have generally been attributed to an aridifying climate, but in many basins flows can also be highly impacted by irrigation. We developed a 35-year dataset consisting of streamflow, climate, irrigated area, and crop water use to quantify the effects of both climate change and irrigation water use on streamflow across 221 basins in the Colorado, Columbia, and Missouri River systems. We demonstrate that flows have been altered beyond observed climate-related changes and that many of these changes are attributable to irrigation. Further, our results indicate that increases in irrigation water use have occurred over much of the study area, a finding that contradicts government-reported irrigation statistics. Increases in crop consumption have enhanced fall and winter flows in some portions of the Upper Missouri and northern Columbia River basins, and have exacerbated climate change-induced flow declines in parts of the Colorado basin. We classify each basin's water resources sustainability in terms of flow and irrigation trends and link irrigation-induced flow changes to irrigation infrastructure modernization and differences in basin physiographic setting. These results provide a basis for determining where modern irrigation systems benefit basin water supply, and where less efficient systems contribute to return flows and relieve ecological stress.

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Irrigation is a critical component of large-scale agriculture and allows for food and fiber production in areas where insufficient precipitation would otherwise inhibit crop growth. About 86 km³ yr⁻¹ of water is applied to irrigated crops annually in the Western U.S., representing nearly 90% of total human water consumption in the region¹. This practice, in turn, supports over 75% of commodity sales on less than 25% of harvested land². The waters of the Colorado, Columbia, and Upper Missouri river systems are perhaps the most important natural resources in the region, supporting a population of 20 million people and an economy of nearly a trillion dollars annually; over 75% of irrigation water in this region is drawn from surface water sources^{3–5}.

Many irrigated regions across the west continue to expand in area and intensify irrigation water use despite ongoing and projected threats to water supply by humans and a changing climate. Further, ecological impacts (e.g., fish mortality) have been linked to irrigation withdrawal for food production in the region, implying a human-ecological use tradeoff in water scarce systems⁶. Overall, the quantity of irrigation water applied has declined over the past 40 years as more efficient (i.e., greater fraction of applied water used by plants) and advanced irrigation systems have been adopted⁷. However, in a ‘paradox of irrigation efficiency’, reduced irrigation withdrawal and application requirements have led to higher consumptive irrigation water use (IWU; i.e., irrigation-derived water lost irretrievably to the atmosphere through crop evapotranspiration). This results in reductions in downstream water supply as crop irrigation is optimized for production^{8–10}.

The consequences of the efficiency paradox are exacerbated by climate change-induced increases in crop water requirements which may lead to increased evapotranspiration (ET) and reduced runoff at the basin scale^{11,12}. Further, climate change has altered important natural hydrological processes that affect streamflow: precipitation, evaporative demand, evapotranspiration, formation and melting of snowpack, and groundwater recharge^{13–19}. While the implications of climate-induced changes to surface water supply are widely recognized in the scientific literature, and process-based assessments of irrigation impacts on water resources have been made, a systematic, empirical, and spatiotemporally resolved examination of irrigation—our society’s greatest hydrological intervention—has not been undertaken in the context of changing surface water availability in the region^{20–23}. Studies demonstrating irrigation impacts on streamflow across the Western U.S. are few and limited to relatively short periods at the basin scale^{24–26}, hindered by coarse spatiotemporal information, or dependent on proxies for crop water use^{6,7,27–29}. Advances in scalable evapotranspiration and irrigation detection algorithms using long-period, high resolution satellite remote sensing now enable the systematic estimate of crop water use at continental scales^{30,31}.

In this study, we developed a 35-year dataset consisting of high-resolution climate, irrigation, and evapotranspiration data alongside streamflow, interbasin transfer, and reservoir storage records for 221 subbasins in the Colorado, Columbia, and Missouri river systems. We determined the characteristic climate response period of monthly streamflow and show that climate change is impacting subannual streamflow in regionally organized patterns and across basin scales. Our analysis suggests that crop irrigation can mediate or exacerbate climate-induced changes to flow and may contribute to streamflow change in the absence of climate change effects. We summarize our results by providing an estimate of sustainability that is sensitive to water supply, use, and climate change. Ultimately, our results map the basin-specific consequences of the irrigation efficiency paradox, characterize the trajectory of surface water sustainability, and

provide a means to evaluate the likely impacts of irrigation management decisions on streamflow.

Results

The objective of this analysis is to understand the sustainability of irrigation water resources across the Western U.S. We define sustainability in the context of trends in both surface water flows and irrigation water use, the principal water supply and use in the region, while accounting for climate change and basin scale irrigation water use-to-availability ratio. Below, we describe our hierarchical approach to evaluating sustainability, ultimately resulting in spatial information that can inform future water management across the West.

Climate and streamflow relationships in irrigated basins. We quantified climatic drivers of streamflow using linear regression of the climatic water balance (CWB; reference evapotranspiration [ET_r] minus precipitation) and monthly flow over the basin-specific climatic aggregation period [Supplementary Note 3.1, Supplementary Fig. 1]. Unsurprisingly, basin-specific models of CWB and streamflow indicate they are inversely related; 96.8% of significant relationships exhibited a negative slope demonstrating that drier climatic aggregation periods yield lesser volumetric flow [Supplementary Data 1, 2]. The flow-CWB relationship explains the majority of monthly flow variance ($r^2 > 0.5$) for at least 1 month of the year at 97% of the irrigated basins in our study. Model explanatory power was lowest in February flows (median r^2 : 0.41, interquartile range [IQR] 0.23) and was highest in June (median r^2 : 0.69, IQR 0.19).

Streamflow trends. Temporal trend analysis using Bayesian linear regression (i.e., the change in flow over time [Supplementary Note 3.3, Equation 2]) revealed that monthly flow volumes have experienced significant changes during the study period; nearly all irrigated basins experienced monthly discharge changes during at least 1 month across our study area [Supplementary Fig. 2a, Supplementary Data 3]. The Colorado basin experienced the most widespread and seasonally persistent declines in flow, especially along the major tributaries of the west slope (e.g., main stem Colorado and San Juan rivers). Major drainages within the Missouri (e.g., Yellowstone, Missouri rivers) experienced increases in flow in the spring and summer. More detailed description of flow trends can be found in Supplementary Note 4.

Temporal trends in climate-normalized flows (i.e., the time component of the bivariate Bayesian linear regression of flow as a function of climate and time [Supplementary Note 3.3, Equation 7]) revealed significant changes in flow unrelated to climate, mostly in the northern regions of the study area (i.e., Pend Oreille, Missouri, and Yellowstone rivers). Widespread flow increases were observed in the upper reaches of the Missouri and around the Columbia, except in the Snake River basin [Supplementary Fig. 2b, Supplementary Data 4]. Of the 30 gages with negative median trends in monthly climate-normalized flow, the Snake River showed the most seasonally persistent and systemic response, with negative trends found along the lower length of the river, generally during the winter and spring.

Irrigation water use trends. Volumetric IWU has represented a large fraction of total available surface water in the most heavily irrigated basins since the beginning of our study period in 1987 [Fig. 1]. The mean annual ratio of April – October IWU to annual flows at the outlets of major basins range from 0.02 on the Pend Oreille River to over 0.6 on the Snake River. In other words, the volume of water used for IWU represents an impressive 60 percent of the water flowing through the Snake River at the Weiser,

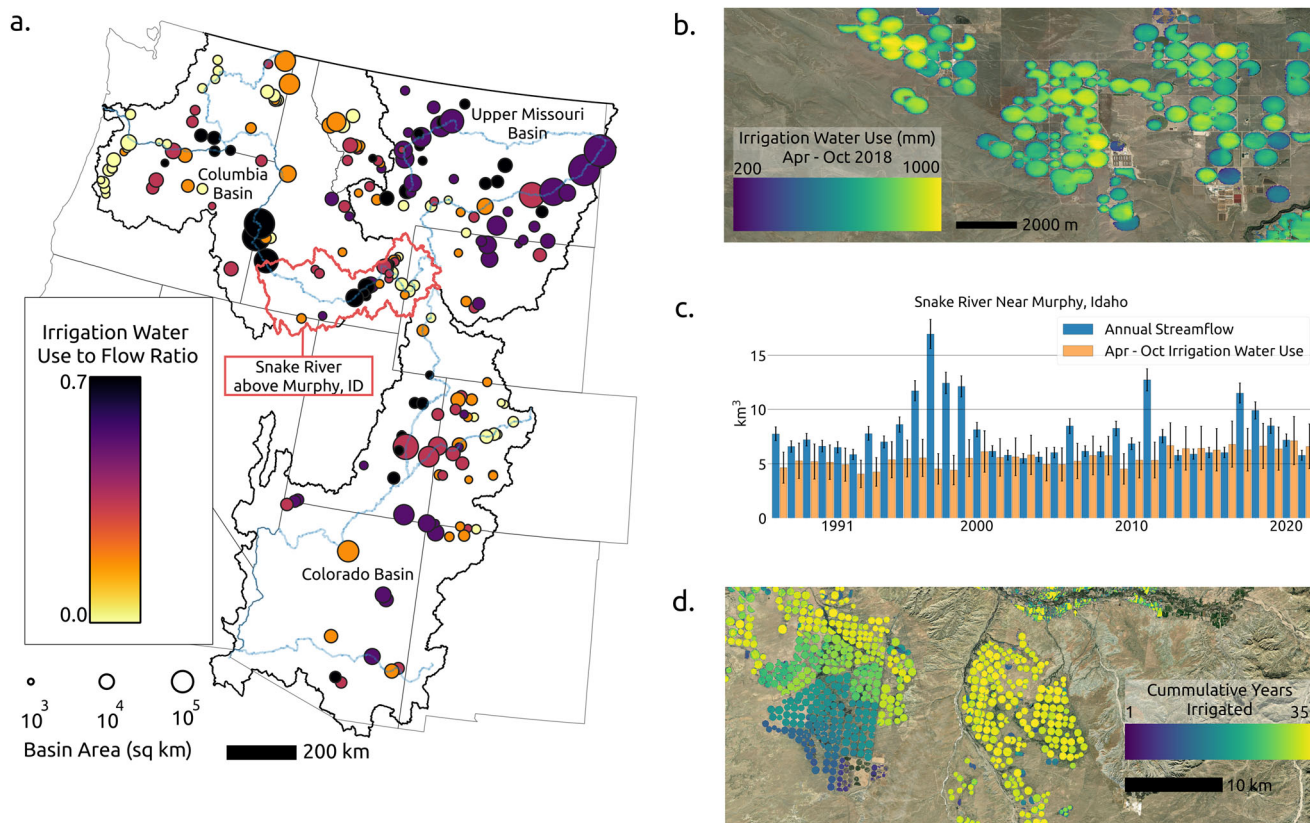


Fig. 1 The magnitude of irrigation compared to flow. The 1987–2021 mean annual flow-to-irrigation water use ratio (dimensionless) at 221 gages draining irrigated basins is shown (a), with the region of the Snake River Basin drained at Murphy, Idaho highlighted in red (USGS Gage 13172500). Symbols are scaled to drainage area. Detail view of 30 m resolution Landsat satellite-based crop consumption estimates in the Snake River Plain of Southwestern Idaho is shown in (b). Annual volumetric discharge at Murphy, Idaho (c), with irrigation water use during the period April 1st to October 31st within the basin. Error bars are shown around estimates of flow and irrigation water use. An example of rapid expansion of irrigated area over the study period in northwest New Mexico is shown in (d).

ID gage annually. Increases in IWU were widespread in terms of all metrics we tested; total IWU, IWU within the perennially-irrigated domain (irrigated all years 1987–2021), and climate-normalized IWU (i.e., the time component of the bivariate Bayesian linear regression of IWU as a function of climate and time [Supplementary Note 3.3, Equation 5]) all showed generally positive trends [Supplementary Fig. 3]. Increases in total IWU were experienced across the Missouri and Colorado systems, but mixed in the Columbia, where decreases occurred in the Cascades. In nearly all cases, IWU increases are associated with the expansion of irrigated area [Supplementary Fig. 4]; of the 15 largest irrigated basins in the study, 12 experienced significant increases in irrigated area. Increases in IWU are further associated with increasing aridity in the Northern Rockies and the Colorado River Basin (i.e., aridification, [Supplementary Fig. 5]).

Stream response to irrigation water use. We found IWU was a significant predictor of climate-normalized flows for at least one month at 90% of analyzed basins [Fig. 2, Supplementary Data 5]. Our analysis identified bidirectional regional and seasonal patterns; increased flows were associated with increased IWU in the Upper Colorado and Missouri basins in the winter, while increased summer flows were less common in large basins, but were detected at smaller basin scales in the headwaters of each system. The largest basins generally experienced flow decreases associated with increased IWU in the summer, while many smaller basins had mixed flow responses to IWU. Over 60 of the study basins experienced IWU-associated impacts in opposite

directions from summer to winter. For example, the two largest basins with this response were the Pend Oreille and the Yellowstone Rivers, both of which see reduced flows in the summer and greater flows in the winter subsequent to increased IWU.

Discussion

Our results show that in many basins, irrigation is causing changes to streamflow, sometimes in opposition to climate change (i.e., increases in sub-annual streamflow despite climate aridification). This response varies from basin to basin, and may increase or decrease flows during different times of the year. Our results indicate that in some basins, water returns to rivers from irrigated lands after some delay, while in others, the water is effectively removed from the basin and ‘lost’ to ET. We posit that enhanced sub-annual flows occurring after the irrigation season, and subsequent to irrigation intensification, are the result of increased groundwater storage and delayed release via return flow to nearby streams. We further suggest that these responses provide information that could allow for targeted irrigation expansion of infrastructure type, timing, and intensity with an understanding of potential surface water consequences. In areas where applied water is lost to further in-basin uses (e.g., lost to ET), irrigation infrastructure should be made as efficient as possible with the intent of minimizing avoidable non-beneficial consumptive uses (e.g., excessive spray and canopy interception losses³²). Conversely, in areas where sub-annual flows are enhanced by irrigation systems, intensification of inefficient irrigation systems (e.g., flood irrigation) may benefit streams in the

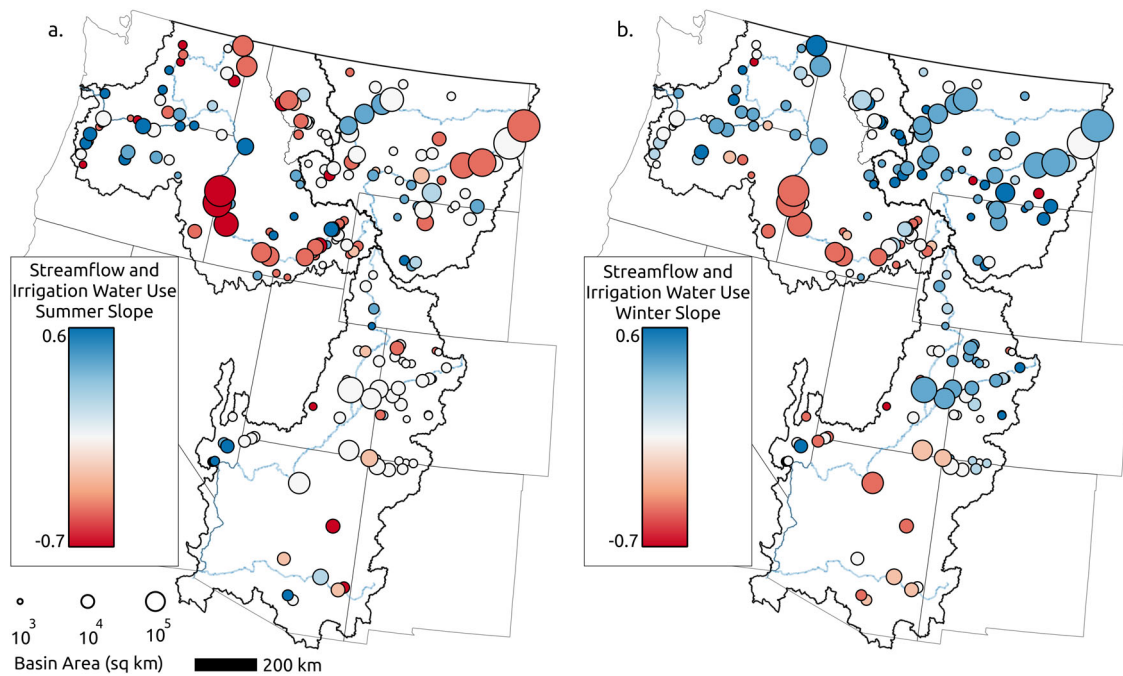


Fig. 2 The flow-irrigation water use relationship. The summer (May through October; **a**) and winter (November through March; **b**) climate-normalized flow-irrigation water use relationship, where flow is a function of irrigation water use in preceding growing season months, and is displayed as the median of monthly significant relationships. Significance is based on gage- and month-specific Bayesian linear univariate (**a**) and bivariate (**b**) models, where significance is based on the highest credible interval of the posterior distribution of slopes; the relationship is significant where 95% of posterior slopes are of a single sign (i.e., positive or negative). Irrigation water use, climatic water balance, and flow were scaled from 0 to 1 prior to analysis (slopes are dimensionless). Symbols are scaled to drainage area.

late summer when return flows of groundwater buffer low flow and high temperatures³³. No two basins are the same and decisions to mitigate declines in water resources must be based upon the interplay of a basin's unique hydrological properties, irrigation systems, climate change trajectory, and multiple and often competing uses of water.

Disentangling climate change and irrigation impacts on streamflow. As expected, the annual streamflow variability in irrigated basins across the Western U.S. is primarily driven by climatic variability³⁴ [Supplementary Data 2]. The significant declines in flow around the Colorado River basin and increases in flow in the Missouri basin coincide with the regions' respective drying and wetting climates [Supplementary Figs. S2, S5]. Interestingly, streamflow has changed in opposition to an obvious climate change signal in 83 basins, indicating the influence of additional forcings (e.g., changes in precipitation intensity, riparian and basin-scale land cover, or the operation of small-scale reservoirs).

There has been an intensive (depth) and extensive (area) increase of irrigation over our study period; it is now more intense, more temporally persistent, covers more of each field, and has expanded into the margins of existing irrigated regions across the west [Supplementary Figs. 3, 4]. This finding contradicts commonly cited county-based irrigated area estimates by the U.S. Department of Agriculture (USDA), which documented only a modest 2% expansion of irrigated area from 1987–2017 in the study area, and a decline in irrigation water application^{1,35}. The limited areal expansion of irrigation reported in survey statistics was concurrent with a nearly two-fold increase in the area under pressurized irrigation systems (e.g., center pivot systems) in the 17 Western states, while gravity-fed systems (e.g., flood) saw a decrease in area of nearly 50%⁷. While systematic and

methodologically consistent, USDA reporting of irrigated area and applied irrigation volumes are a poor proxy for IWU, and it appears the widespread reliance upon such data has led to the operation of the efficiency paradox at scale going unobserved. The increasing intensity of IWU, concurrent with the remarkable expansion of modern irrigation systems across the region, and with regional increases in CWB appear to have outweighed any retraction in irrigated area due to suburban development or water conservation efforts. Trends in climate-normalized IWU and IWU in perennially irrigated areas further support the notion of the counterintuitive increase in water use accompanying increases in irrigation efficiency, despite reductions in irrigation water applications, and are consistent with previous work at smaller scales^{10,36}.

Climate-normalized flow responses to IWU show that streams are sensitive to the expansion and intensification of irrigation operations [Fig. 2], suggesting that many observed streamflow changes are due to irrigation intensification. Our results indicate that the most widespread negative impacts of increased IWU on flow occur during the summer, which may imply strong ecological implications³⁷. Impacts on winter flows have distinct systemic patterns, where unidirectional, multi-gage impacts are noted along the Pend Oreille, Snake, and Upper Missouri rivers (negative responses), while the Yellowstone and Green also show organized responses at multiple gages (positive responses). In both seasons, response directions and timing are highly variable from basin to basin, and while we emphasize system-wide patterns here, the larger basins are likely integrating bi-directional influences and noise resulting from our simplified modeling approach.

Trends in climate-normalized flows indicate that concurrent trends in irrigation are contributing to streamflow changes in many of the study basins. The widespread positive trends observed in this study are focused around October and November

flows, suggesting that irrigation during the summer can increase flows later in the season [Supplementary Data 4]. We suggest this timing is the result of return flows of irrigation water after some delay, as has been modeled in real and conceptual systems by other workers^{38,39}. The positive influence on flows later in the season in some basins suggests that IWU may augment flows when they are at their lowest, providing valuable ecosystem services during times of stress for aquatic and adjacent terrestrial ecosystems⁴⁰. Positive impacts were not ubiquitous across the region; negative trends on the San Juan river suggest water diversions do not increase late season flows and imply IWU is exacerbating the negative impacts of an aridifying climate in the region, further diminishing instream flows. On the Snake River, flow trends in the lower basin are opposite than what we would expect given the slight wetting of the climate and increases in flows in upper tributaries. It appears IWU in the Snake River basin has overcome increased water availability and caused flows to decline over the study period.

Why do basins respond differently? The Missouri and Snake River basins are illustrative of IWU impacts on contrasting streamflow trends. The Snake appears to have undergone a more clear wetting trend relative to the Missouri Basin, while both have seen increases in IWU [Supplementary Figs. 3, 5]. In spite of these climate and IWU trends, the Missouri has mostly experienced increases in flow while the Snake has seen decreases [Supplementary Fig. 2]; due to physiographic and management differences. For example, in the Eastern Snake River Plain, there has been a rapid conversion of irrigation infrastructure to more efficient center pivot systems, representing a transition from about 35% in 1986 to about 75% 2015^{41,42} [Supplementary Note 2]). Snake River basin irrigation systems are located on average 8 km from the nearest stream in areas hydrologically connected to the river via regional aquifer flow paths that operate on long time scales⁴³. Further, 50% of irrigated area overlays less permeable basalt formations with thick unsaturated zones⁴⁴. In summation, Snake River irrigation is more efficient, is less likely to recharge the subsurface, and the subsurface aquifer is less hydrologically connected to the river than the Upper Missouri system^{43,45}. This causes a diminished and long-term delay in return flows, potentially explaining the lack of a lagged, positive streamflow response to increases in irrigation during the time scales assessed in this study (up to 60 months). In contrast, the Upper Missouri Basin in Montana saw mixed streamflow impacts, with more frequent detection of lagged increases in streamflow due to irrigation on short time scales (Missouri Basin median lag: 5.2 months), especially along the Yellowstone River. Here, only 40% of the basin's irrigated lands utilized center pivot in 2019, over 50% of irrigation overlies unconsolidated alluvial and periglacial aquifers, and irrigated fields average only 2.7 km from the nearest stream^{46,47}. The Upper Missouri irrigation is less efficient due to the slower adoption of modern irrigation systems, likely resulting in more groundwater recharge during periods of intense irrigation. Finally, irrigated regions in the Missouri River basin overlay aquifers that are more immediately hydrologically connected to neighboring streams, likely leading to more robust return flows on sub-annual timescales⁴⁷.

Sustainability of water resources. Comparison of trends in flow and IWU indicate the trajectory of water resources across the region and provide a basis for classifying irrigated basins in terms of water resources sustainability [Fig. 3c]. Declining flows and increasing IWU are found at 43 gages, focused in the Snake and Colorado River basins, and represent the least sustainable water resources trajectory identified in this study. The Snake further

stands out as a highly appropriated system; the largest sub-basins far exceed the threshold of 0.4 use-to-availability ratio at which a basin may be considered under water stress^{28,48,49}. Surprisingly, the most numerous classification (60 gages) is found where IWU and flow trends are both increasing, most widely observed in the Missouri basin (an area with widespread flood irrigation) and scattered through the Columbia and Colorado basins. The most sustainable trajectory is focused in the western Columbia river basin, where water resource pressure is alleviated due to less IWU demand which subsequently increases streamflow (13 gages; Figs. 2, 3). There are only a few cases of declining flows and declining IWU (3 gages). The trends identified here, therefore, suggest that the Upper Missouri system follows a more sustainable trajectory, where increased water use is associated with generally increasing flows. This is in contrast to many of the major tributaries in the Colorado basin and the Snake River, where water use, starting from an already very high baseline, has increased despite diminishing supplies and ongoing efforts to make water use more sustainable⁵⁰. In fact, it appears IWU and associated management actions on the Snake River have overcome a slight wetting trend in the fall and winter, which would otherwise be expected to increase flow. However, a generally aridifying climate appears to play a primary role in the decline in flow throughout the Colorado River basin, though it appears that increasing IWU in the San Juan has exacerbated these impacts.

Our findings provide empirical evidence of the widespread occurrence of the processes detailed by previous work on the Smith River in Montana and in conceptual modeling efforts, specifically that irrigation return flows may represent a large fraction of late season flows and result in sub-annual enhancement of flows in riparian irrigated systems^{24,38,39}. This study is the first of its kind to show the comparative influence of such processes across the Western US. The findings here supply a nuanced, high resolution, sub-basin scale description of the impact of changes in irrigation intensity on stream flow, affirming and resolving results of process-based model analysis in previous work at larger scales^{20–23}. The development of field-scale, remote sensing-based IWU data provides insight into changes in consumptive water use by agriculture that has gone undocumented by the USDA, as the survey methods in use currently only track irrigated area and water withdrawals, both of which can remain constant as changes in climate and irrigation infrastructure change actual consumptive use and thus basin water balance.

Much of our study area has experienced a deepening water crisis since the onset of drought two decades ago⁵¹. Under these conditions of non-stationarity, it is crucial to configure our irrigated agricultural systems in such a way that they become resilient to climate change and flexible in their intensity of water use⁵². Our results show that, given the unique response of basins to irrigation intensification and climate change, agricultural paradigms viewed as non-efficient, such as flood irrigation, may in fact be preferable in regions such as the Missouri basin. Further irrigation development in areas experiencing surface water supply declines should be considered in the context of basin physiography and likely streamflow impacts of irrigation expansion and intensification. This study advances that imperative through the spatiotemporal description of such basin-specific characteristics in the context of climate change and human water use.

Methods and Protocols

Methods and Protocols are discussed at length in the Supplementary Note.

Base datasets. We calculated monthly mean flow over the period 1987–2021 at 221 gages from the United States Geological Survey

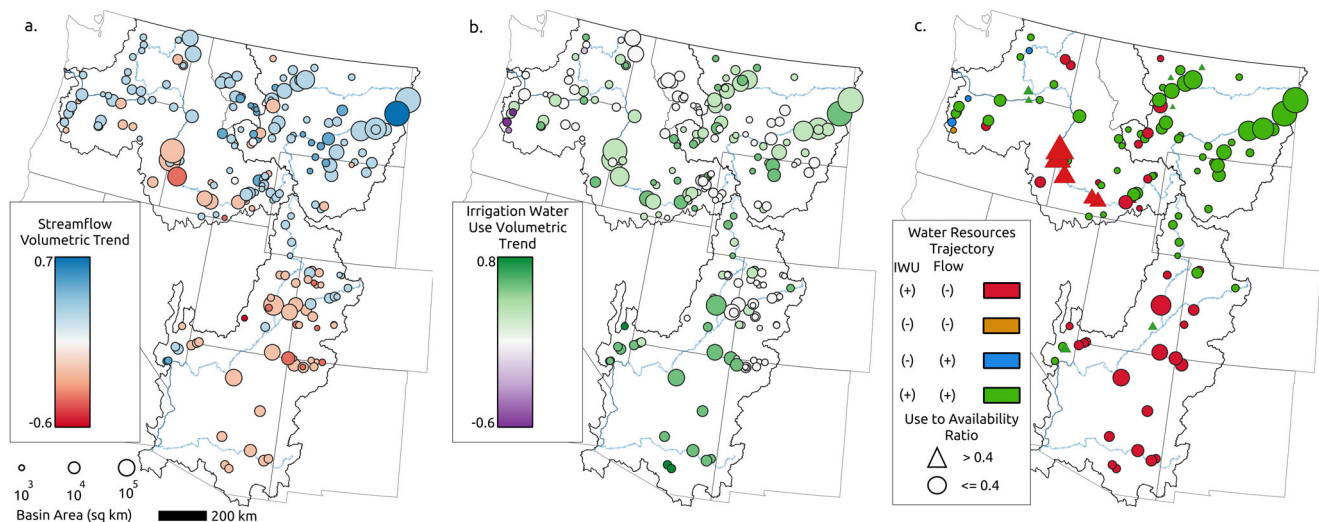


Fig. 3 Trends in flow, irrigation water use, and estimated sustainability. Trends in (a) streamflow and (b) irrigation water use (IWU) 1987–2021 at 221 gages draining irrigated basins. Trend significance is based on 95% of the highest credible interval of the posterior distribution of slopes in a, b; the relationship is significant where 95% of posterior slopes are of a single sign. Water resources trajectory in (c) shows in which basins significant relationships in flow and irrigation water use were found, and classifies them according to the slope of each trend, indicating basin water use sustainability. Flow and irrigation water use were scaled from 0 to 1 prior to analysis (slopes are dimensionless). Symbols are scaled to drainage area.

National Water Information System⁵³, accounted for reservoir storage and interbasin transfers after^{54,55}, and aggregated gridded climate, irrigated area, and evapotranspiration data for the contributing watershed above each gage [Supplementary Note 1, Supplementary Data 1]. We calculated CWB using precipitation and ETr data from the GridMET product, a daily 4 km modeled meteorological dataset⁵⁶. We estimated monthly IWU by masking SSEBop satellite-based ET to the IrrMapper annual irrigation mask (both 30 m resolution), and subtracting the ‘naturalized’ ET signal using our monthly, 1 km resolution effective precipitation estimates^{57,58}.

Climate-flow period. We calculated each basin’s monthly characteristic climate response time by finding the maximum correlation (Pearson’s R-squared) between monthly flow and CWB (reference evapotranspiration minus precipitation) aggregated over an iteratively expanding period of consecutive months, ranging from the coincident, overlapping flow time period and expanding into the past up to 60 months. The climate period with highest correlation to a given month’s flow was considered characteristic of the basin during that month and defined the climate-flow period used to model climate-normalized flow in subsequent analysis [Supplementary Note 3; Supplementary Fig. 1, Supplementary Data Table 2]. Using this approach, we applied a specific climate-flow period for each month’s flow at each gage, giving 12 climate-flow periods for each of the 221 gages.

Flow response to IWU. We used Bayesian bivariate linear regression to control for climate variations (‘climate-normalized flows’) to test for significant response of flow to IWU [Supplementary Note 3]. We derived uncertainty estimates for both variables by calculating basin-specific or study-wide IrrMapper, effective precipitation, SSEBop, and gridMET error for use as uncertainty approximations in our irrigated area, IWU, and CWB estimates [Supplementary Note 1]. We used the PyMC implementation of the Hamiltonian Monte Carlo method to obtain a sequence of randomly drawn samples and generate a distribution of linear model parameters (i.e., slopes for each predictive variable and intercept) describing our data⁵⁹. We extracted the posterior

chain (final 1000 iterations) of the Markov Chain Monte Carlo (MCMC) samples to determine the highest credible interval of slopes. We considered regressions where 95% of the credible interval of posterior slopes are of the same sign to be significant⁶⁰.

Trends analysis. We used Bayesian univariate linear regression to test for significant trends in total monthly streamflow, IWU, irrigated area, and CWB, again using the 95% credible interval to test for significance. We further tested flow trends by using Bayesian bivariate linear regression using CWB as an additional predictor to find significant climate-normalized trends. We used a similar approach with time trends of IWU, but used the concurrent month CWB to find climate-normalized IWU. We used our uncertainty estimates for each dataset in the Bayesian time trend analysis, as described above and in Supplementary Notes 2 and 3.

Data availability

Model inputs used to perform this work are available in the Zenodo repository at <https://doi.org/10.5281/zenodo.10119415>.

Code availability

The analysis performed in this paper can be replicated using our Python repository at https://github.com/dgketchum/irr_impacts/tree/comms_env.

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Author contributions

D.K., Z.H., and K.J. designed research; D.K. performed research and analyzed data; D.K. and J.H. contributed software; D.B. and Z.H. reviewed software; D.K., Z.H., and K.J. wrote the manuscript, D.K., Z.H., D.B., J.H., and K.J. edited the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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