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LETTER

Archetypal flow regime change classes and their associations with anthropogenic drivers of global streamflow alterations

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Abstract

Streamflow—a key component of the water cycle—is experiencing drastic alteration due to human actions. The global extent and degree of this change have been widely assessed, but understanding of its drivers remains limited because previous global-scale approaches have largely relied on modelled hypothetical scenarios. Here, we advance this understanding by providing an observation-based association analysis of streamflow change and its drivers. We use observed streamflow data in 3,293 catchments globally and combine them with data on precipitation, evapotranspiration, water use, and damming. Building on a robust annual trend analysis covering years 1971–2010, we first determine flow regime change (FRC) classes, and then use them to investigate associations between streamflow change and its drivers. We find that 91% of all catchments are assigned to four main FRCs, which indicates globally consistent flow regime changes. By associating driver trends with the FRCs, we further characterise them by trends and changes in the four investigated drivers. We find that FRCs depicting decreasing streamflow quantity and variability are strongly associated with direct human drivers, either water use or damming. In contrast, associations with indirect drivers (precipitation and evapotranspiration) are more dominant in FRCs that depict increasing streamflow quantity and variability. Our key advance is that our comprehensive, observation-based association analysis substantiates the model-based findings of previous global-scale studies, and thus adds detail and validation to their interpretations. This may further support developing and adopting efficient measures to mitigate streamflow change and its subsequent impacts across scales.

1. Introduction

The global freshwater cycle has undergone drastic, anthropogenically driven changes since industrialisation. Globally widespread streamflow alterations are perhaps some of the most prominent examples of this change (Gudmundsson *et al* 2021, Yang *et al* 2021, Virkki *et al* 2022). These alterations have become so pervasive that recent studies have suggested they undermine the Earth system functions related to freshwater and elevate risks related to diminishing resilience and stability of the Earth system (Gleeson *et al* 2020, Richardson *et al* 2023, Porkka *et al* 2024). To effectively mitigate these risks, it is important to disentangle the underlying drivers behind the remarkable global change in streamflow.

The key drivers of streamflow alteration are related to climatic factors modifying water availability and human actions on the land surface diverting the flows of this water. Climate change and variability alter the spatiotemporal distribution of precipitation and evapotranspiration (Adler *et al* 2017, Zhang *et al* 2023), and land cover change can further attenuate or amplify these impacts by modifying the land-atmosphere moisture exchange (Wang-Erlandsson *et al* 2018, Theeuwen *et al* 2023). These indirect drivers affect runoff generation and, ultimately, streamflow volume. Once streamflow is generated from the available water, it may be altered by direct human actions. Consumptive water use, mainly for agricultural purposes, may appropriate and divert streamflow from its natural course (Wada and Bierkens 2014, Huang *et al* 2018), and flow regulation by dams and reservoirs may change the temporal distribution of streamflow, often towards homogenised flow regimes (Poff *et al* 2007, Best 2019, Grill *et al* 2019).

Studies across scales have assessed the contributions of different drivers on streamflow alterations. Yet, global-scale studies often lack the depth and detail of local and regional approaches that can, for instance, incorporate highly specialised hydrological modelling setups and extensive data (Dennedy-Frank and Gorelick 2019, Horton *et al* 2021) or advanced empirical models (Levy *et al* 2018, Chagas *et al* 2022). Instead, global studies on streamflow change often focus on describing the hydrological outcome and attaching driver attribution to this by, for example, qualitative discussion (Porkka *et al* 2024), static information on human drivers (Yang *et al* 2021), or incorporation of a limited set of drivers (Zhang *et al* 2023). In global studies whose main objective is explicit driver attribution, perhaps the most prominent approach is to utilise hydrological modelling scenarios with variable driver configurations (Veldkamp *et al* 2018, Gudmundsson *et al* 2021, Kåresdotter *et al* 2022, Pastor *et al* 2022). This general approach is based on running globally applicable hydrological models in a suite of scenarios, including or excluding one or more drivers at a time. Model outputs are then compared to assess how much each inclusion or exclusion affects modelled streamflow, and the differences between scenarios are attributed to the distinct drivers.

The predominant global-scale driver attribution approach, however, suffers from two major drawbacks. First, global hydrological models can strictly assess the hydrological impacts of mechanisms and interactions implemented in the models, which are relatively simplified with variable parameterisations and uncertainties (Telteu *et al* 2021). Second, the assessed scenarios are largely hypothetical—for instance, a typical control scenario in global hydrological modelling may assume static climate and dynamic water use (Frieler *et al* 2024). These scenarios, thus, do not necessarily represent hydrological systems that have existed in the past, which further deepens the dependence on how hydrological processes are mechanistically implemented in the models. This is especially relevant because the direct and indirect drivers depend on each other, and streamflow changes have been observed more commonly in catchments that are influenced by both types of drivers (Yang *et al* 2021). We therefore argue that the hypothetical model-based approaches should be complemented with observation-based approaches to improve the understanding of how streamflow regime changes link to anthropogenically related drivers at the global scale.

This study overcomes the limitations of existing global-scale driver attribution studies by composing a near-global, observation-based association analysis of streamflow change and related drivers. We present an annual trend analysis covering years 1971–2010, utilising streamflow observations and global data on four drivers: precipitation, evapotranspiration, water use, and damming. Our large sample of catchments with streamflow observations across the globe allows for robustly associating common streamflow regime alterations with these drivers. This approach is less assumptive and dependent on modelling scenarios than existing global-scale approaches and balanced between using historically coherent evidence and a large enough sample size. Our approach thus allows us to associate streamflow change and its related drivers at the global scale in a way that substantiates and advances the existing, model-based studies.

2. Methods

Figure 1 presents the methodological outline of this study. To compose a global sample of streamflow data, we queried the Global Streamflow Indices and Metadata Archive (GSIM) (Do *et al* 2018, Gudmundsson *et al* 2018) to find catchments with a sufficiently long and reliable monthly streamflow record. We then determined flow regime change (FRC) classes that depict streamflow regime alteration based on linear trends in four annual streamflow metrics. We similarly derived linear trends in the indirect and direct drivers using 0.1-degree resolution monthly precipitation and evapotranspiration data from ERA5-Land (Muñoz-Sabater *et al* 2021), 0.5-degree resolution monthly total consumptive water use data from Huang *et al* (2018), and dam records from GeoDAR (Wang *et al* 2022). Finally, we grouped driver trends using four main FRC classes to reveal how streamflow change and its drivers are associated.

2.1. Data preparation

The GSIM database collates streamflow observations from national authorities and international collections, covering over 35,000 streamflow records in a consistently formatted and quality-controlled collection (Do *et al* 2018, Gudmundsson *et al* 2018). Out of these, we selected all mean monthly streamflow records that fulfilled

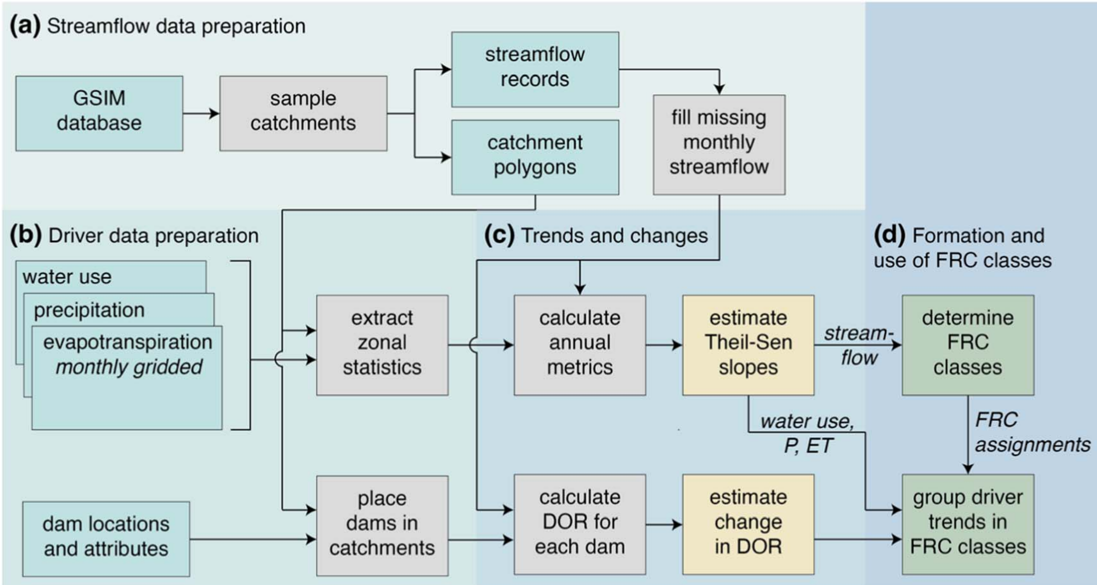

Figure 1. Methodological outline of the study. Streamflow data were prepared by sampling catchments and filling in missing monthly data entries. (a) Driver data were prepared by extracting zonal statistics (for precipitation; P, evapotranspiration; ET, and water use) and querying dam points within catchment polygons. (b) Monthly values were then transformed into annual metrics, followed by an assessment of linear trends using Theil-Sen slopes (streamflow, P, ET, water use) and absolute change in the degree of regulation (DOR) for dams. (c) Finally, trends in four streamflow metrics were used to assign catchments to flow regime change (FRC) classes that were subsequently used to group driver trends and changes to associate streamflow change with its drivers (d).

three conditions: (1) the catchment area is greater than 1,000 km^2; (2) streamflow observations cover at least 30 years within 1971–2010; and (3) more than 50% of monthly values between the first and last month of record are available. Although streamflow data were available before 1971 and after 2010, the temporal extent was limited by the driver data availability on water use. Missing monthly streamflow values were filled with the mean of available values of the same month within ±10 years of the missing value. These conditions ensured that the selected catchments were large enough for zonal statistics and that the streamflow records were long enough for fitting linear trends.

To ensure accuracy for zonal statistics, streamflow records flagged as 'caution' were mainly discarded. This GSIM quality flag is marked for records whose delineated catchment area differs from the reported catchment area by more than 50% and for records with no reported catchment area. However, we included 353 records with no reported catchment area in GSIM. This was done by matching the streamflow gauge station and river names with a newer release of the GRDC station catalogue (GRDC 2023) and assessing that the delineated GSIM catchment area had a less than 50% mismatch with the matched GRDC reported catchment area. Duplicate catchments were additionally handled by identifying catchment groups in which all catchments had more than 90% area overlap with each other. In the identified duplicate groups, the catchment with the highest number of monthly streamflow observations was selected, totalling 186 preserved duplicates; 206 redundant duplicates were discarded. Nested catchments (sub-catchments of larger basins) with less than 90% common area overlap were left in the sample and treated as individual catchments.

After applying the above sampling criteria, 3,293 catchment records from GSIM were included, with 2,290 catchments having a full 40-year record from 1971 to 2010 (figure S1(a)). Most records required only little filling of missing monthly streamflow values, as the majority (80%) of all streamflow records had more than 90% of monthly mean streamflow values available (figure S1(b)). Therefore, our sample could be considered robust for assessing streamflow trends. All continents were represented in the selected records; however, most catchments (88%) were in Europe, North America, or South America, which were also the regions that had many smaller nested catchments within larger basins (figure S1(c)).

Gridded precipitation and evapotranspiration data were fetched from ERA5-Land (Muñoz-Sabater *et al* 2021). Although ERA5-Land is a reanalysis product, we chose to use it since it has recently been evaluated as adequate for simulating river discharge (Gebrechorkos *et al* 2024). Gridded sectoral water use data—comprising the irrigation, domestic, electricity generation, livestock, mining, and manufacturing sectors (Huang *et al* 2018)—were summed to total water use. For all these monthly gridded data, we extracted zonal statistics within spatially explicit catchment boundaries provided by GSIM. As all three variables were expressed as water column depths (millimetres/month), we used cell area-weighted mean as the aggregation metric, utilising the *exact_extract* R function (Baston 2022). This function considers partial overlaps between polygon and gridded data, using in summarisation only the fraction of each grid cell that overlaps with the catchment boundary. While this increases the utility of zonal statistics for small catchments and coarse driver data, it also assumes that the respective grid variable value is spread evenly over the grid cell, incurring some uncertainty. In all catchments, the temporal extent of streamflow data dictated the temporal extent of driver data; for each driver, we only considered the years that had streamflow observations. Thus, in an individual catchment, streamflow and driver trends were always computed from the same time period of streamflow and driver data.

The GeoDAR database georeferences approximately 25,000 dam records from the World Register of Dams (WRD) and is currently one of the most comprehensive global databases containing both locations and attributes of large dams (Wang *et al* 2022). Although dam locations are openly available in GeoDAR, dam attributes are proprietary to the WRD. We updated the dam attributes with recent data from the WRD (retrieved on 20 July 2023). Dams within each spatially explicit catchment boundary were queried by point-in-polygon operations, repeating the same procedure also for all nested catchments. Further, the reservoir capacity of each matched dam was related to the total annual volumetric streamflow at the catchment outlet. This corresponds to the commonly used metric 'degree of regulation' (DOR) (Nilsson *et al* 2005). We set the DOR value of each dam to apply from the first month of the year of dam completion, and cumulatively summed the DOR values for each catchment. The cumulative DOR only considered increasing regulation as removed dams are absent in the WRD.

2.2. Trend analysis and flow regime change (FRC) classification

Throughout the analysis, we estimated linear trends using Theil-Sen regression, which is a robust linear regression method that outputs the median of trend slopes between all possible pairs of data points (Hurtado 2020). This makes the resulting Theil-Sen slope less sensitive to outliers. We estimated Theil-Sen slopes using annual metrics, which were computed from monthly streamflow and driver values (except for DOR). For streamflow, we calculated annual metrics and subsequently estimated trends for annual mean, standard deviation, and 5th and 95th percentiles. For precipitation and evapotranspiration, we used annual mean and standard deviation, whereas for water use, we used annual mean only.

Each catchment was assigned an FRC class based on the Theil-Sen slopes of four annual streamflow metrics (table 1; figure S2). Four main FRCs were predefined: decreasing and increasing trends in mean streamflow (depicting quantity) characterised the 'shift down' and 'shift up' FRCs, respectively, whereas decreasing and increasing trends in the standard deviation of streamflow (depicting variability) characterised the 'shrink' and 'expand' FRCs, respectively. Conditions on trend direction were not enforced for one of the four streamflow trends in each FRC (labelled 'unconstrained' in table 1). The four main FRCs thus comprised eight out of sixteen possible combinations that can be derived from trend directions in four streamflow metrics. Catchments with one of the remaining eight trend combinations not covered by the four main FRCs were assigned a class 'other'. This was also done for special cases where the Theil-Sen slope was zero, for instance, when the 5th percentile streamflow was zero throughout the record.

Table 1. Assignment rules for the four main flow regime change (FRC) classes. For each catchment and streamflow metric (mean, standard deviation, high flow, low flow), trends (Theil-Sen slopes) were computed based on annual metrics within the interval 1971–2010, with the sample size ranging from 30 to 40 years, depending on streamflow record length in each catchment (figure S1(a)). Catchments were assigned to an FRC class based on the combination of four Theil-Sen slopes; in the table, 'decreasing' means that the Theil-Sen slope is negative, and 'increasing' means that the Theil-Sen slope is positive. For conditions marked as 'unconstrained', the Theil-Sen slope can be either negative or positive. Should the combination of four trends in a catchment not match any of the four main FRC classes, it was assigned a class 'other'. The Theil-Sen slopes needed not to be statistically significant in the FRC assignments.

Streamflow metric	Flow regime change (FRC) class			
	'Shift down'	'Shift up'	'Shrink'	'Expand'
Mean	Decreasing	Increasing	Unconstrained	Unconstrained
Standard deviation	Unconstrained	Unconstrained	Decreasing	Increasing
High (95th percentile) flow	Decreasing	Increasing	Decreasing	Increasing
Low (5th percentile) flow	Decreasing	Increasing	Increasing	Decreasing

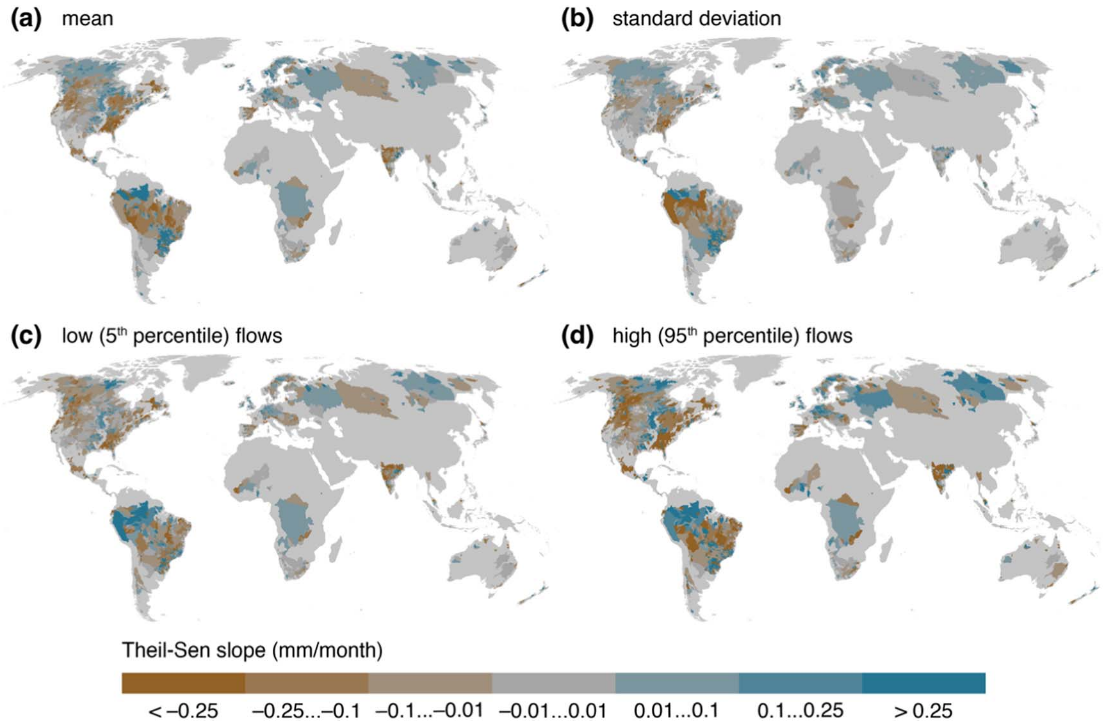

Figure 2. Linear trends in four streamflow metrics: mean (a), standard deviation (b), low (5th percentile) flows (c), and high (95th percentile) flows (d). All trends (Theil-Sen slopes) are computed based on annual metrics within the interval 1971–2010, with the sample size ranging from 30 to 40 years, depending on streamflow record length in each catchment (figure S1(a)). Nested catchments are plotted so that small catchments are drawn on top of larger ones, thus showing the maximum available detail.

3. Results

3.1. Flow regime changes

The key characteristics of a flow regime—the quantity, variability, and typical range of streamflow—exhibit globally widespread change. For all four annual streamflow metrics (mean, standard deviation, and high and low flows), decreasing trends are more frequent than increasing trends (figure 2). Most of the Theil-Sen slopes presented here are not statistically significant, although some statistically significant trends can be seen especially in small catchments (figure S3). When looking at trends in the decreasing direction, some of the most impacted regions consist of the southwestern coast of North America and central Brazil, for instance—here, trends in all four metrics would suggest decreasing streamflow. Contrarily, regions in northern Amazonia and Central Europe, for example, commonly show increasing trends in all four metrics, indicating that streamflow is increasing across all facets of the flow regime.

Catchments assigned to the four FRCs (table 1) comprise 2,986 out of 3,293 (91%) of all catchments (figure 3). The remaining 307 catchments that were not assigned to one of the four FRCs were assigned to the class 'other'. A large majority of all catchments falling into one of the four FRCs indicates that streamflow alteration prevails throughout flow regimes, commonly in one of these four archetypal patterns. The 'shift down' and 'shrink' FRCs are more common than their opposite direction counterparts, 'shift up' and 'expand', across all catchment size groups (figure 3). Additionally, the large majority of 'shift down' and 'shift up' catchments have, respectively, a decreasing and an increasing trend also for standard deviation (table S1). For 'shrink' and 'expand', the fraction of this kind of parallel direction trends for the mean is not equally high, though still a majority (table S1). This would suggest that decreases in streamflow quantity and variability are more common than increases, and that consistent, unidirectional shifts throughout the flow regime (either towards the drying or wetting direction) are the most common FRCs globally.

The 'shift down' FRC is prevalent in central South America and on the eastern and western sides of North America (figure 3), which are regions where also the decreasing streamflow trend slopes are comparatively strong (figure 2). On the contrary, many catchments in the Eurasian boreal zone and northern parts of Canada are assigned to the 'shift up' or 'shrink' FRC class (figure 3). Similarly, the streamflow trend slopes there are moderate to strong (figure 2), although it should be noted that the geographically extensive Eurasian boreal zone is covered by relatively few large catchments ($n \approx 160$; figure S1(c)). Some large basins, such as the Rhine and the

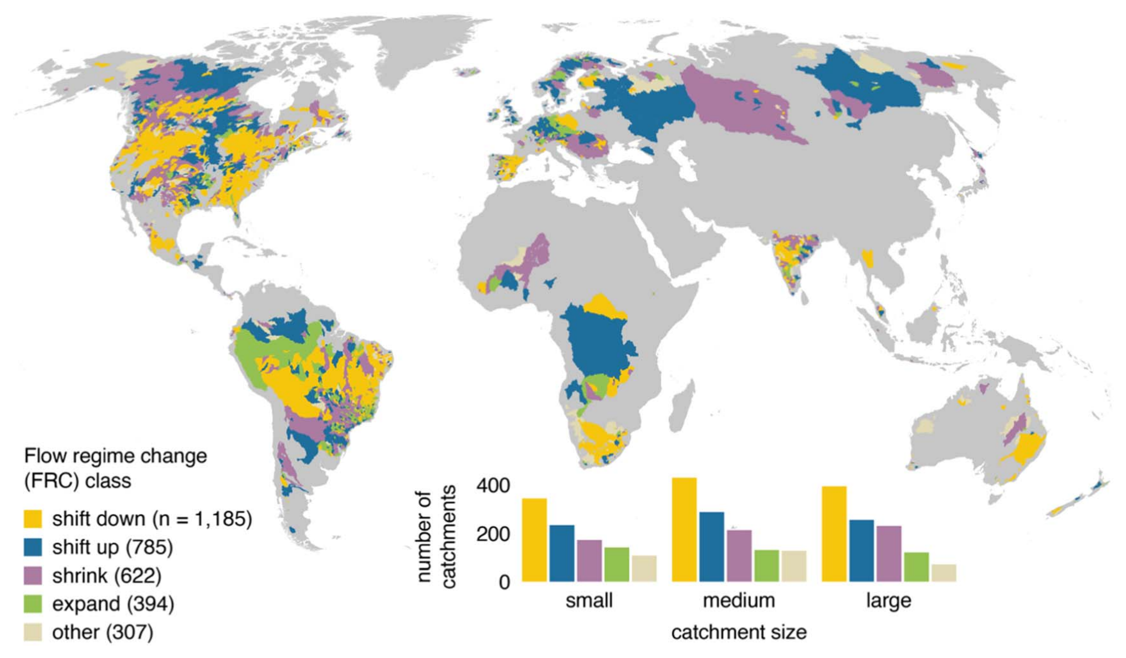

Figure 3. Assignment of flow regime change (FRC) classes for 3,293 catchments globally. The FRCs are determined by the direction of linear trends (Theil-Sen slopes) in four annual streamflow metrics (table 1). Catchments are additionally grouped into three size groups, using a minimum catchment area of 1,000 km^2 in the small catchments group, a catchment area of 2,500 km^2 as the threshold between small and medium catchments, and a catchment area of 10,000 km^2 as the threshold between medium and large catchments. Nested catchments are plotted so that small catchments are drawn on top of larger ones, thus showing the maximum available detail.

Colorado River, have most of their sub-catchments assigned to the same FRC with the main basin ('shift up' and 'shift down', respectively), whereas, for instance, sub-catchments of the Parana and the Saskatchewan rivers represent all four FRCs.

3.2. Driver trends and changes

At the global scale, mean precipitation and evapotranspiration trends are moderately correlated, whereas the standard deviation trends of precipitation and evapotranspiration appear independent (figures 4(a)–(d), figure S4). Although opposite direction trends for mean precipitation and evapotranspiration are visible at large scales in eastern Europe, Siberia, and north-western South America, for instance, trends in parallel direction for these two indirect drivers appear globally prevalent (figures 4(a)–(b)). Mean precipitation trends (figure 4(a)) are the only case for which, among all sampled catchments, decreasing trends are more frequent than increasing trends. In contrast, for the other three climatic variables, increasing trends are more common (figures 4(b)–(d)).

Strong water use trends are concentrated in relatively small regions (figure 4(e)). On the one hand, in southern Asia and in parts of South America, water use trends have been strongly increasing. On the other hand, much of Europe and North America show moderate to strongly decreasing mean water use trends. However, most regions show negligible water use trends—possibly due to their very low absolute water use. Furthermore, a total of 8,435 dams are captured within the sampled catchments, with the heaviest increases in regulation found in large catchments. More than half of catchments (58%) with an area greater than 10,000 km^2 have seen an increase in DOR, whereas the same figure is 29% for catchments below this threshold. Increasing large-scale river regulation during the study period is the most clearly visible in many catchments in southern Africa and southern North America, as well as in the Murray-Darling River basin in Australia (figure 4(f)).

3.3. Associations between FRCs and driver trends

A systematic assessment of associations between the FRC assignments (figure 3) and trends and changes in drivers (figure 4) reveals how the four FRCs not only characterise changes in streamflow regimes but also allow for suggesting possible drivers underlying this change. This association is done here in two stages. Presuming that streamflow regimes are predominantly shaped by the amount and variability of precipitation; figure 5 first investigates how increasing and decreasing precipitation trends are associated with the FRCs. Following this, figure 6 additionally summarises trends in evapotranspiration, water use, and changes in the degree of regulation. These two stages jointly enable a characterisation of FRCs by the most commonly occurring driver trends and changes, relating streamflow change with some of its external drivers.

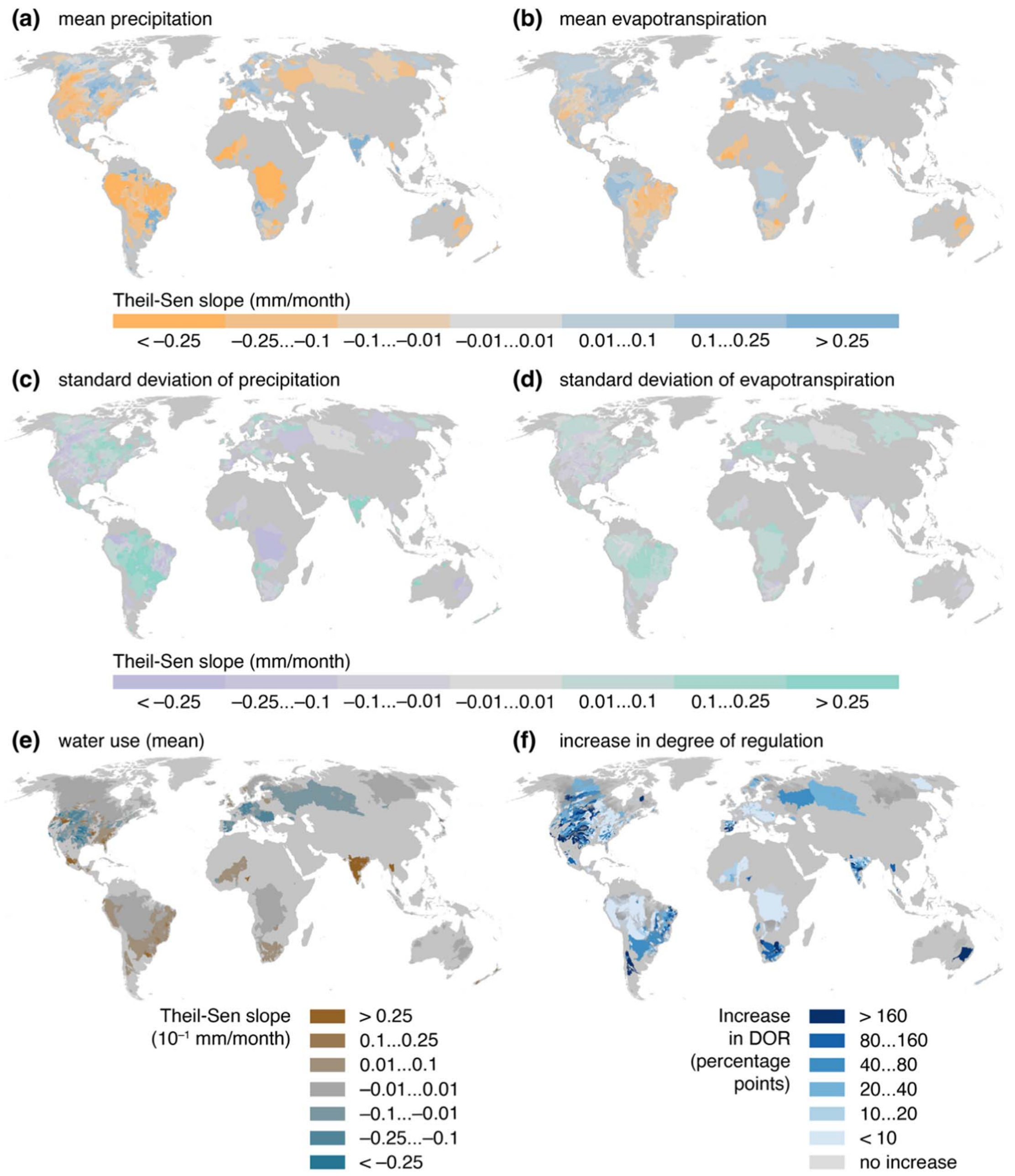

Figure 4. Trends and changes in driver variables: mean precipitation trend (a), mean evapotranspiration trend (b), trend in the standard deviation of precipitation (c), trend in the standard deviation of evapotranspiration (d), mean total water use trend (e), and increase in the degree of regulation (DOR) (f). Trends (Theil-Sen slopes) in panels (a)–(e) are computed based on annual metrics within the interval 1971–2010, with the sample size ranging from 30 to 40 years, depending on streamflow record length in each catchment (figure S1(a)). For dams (f), instead of the Theil-Sen slope, change in time is assessed by absolute increase in the degree of regulation (DOR), measured in percentage points. Catchments that have not experienced an increase in DOR (being mainly sub-catchments of large basins) are overlaid on top of panel (f) with a transparent grey overlay.

The direction of precipitation trends mostly agrees with the direction of streamflow mean or standard deviation trend in each FRC class. For 'shift down' and 'shift up', most catchments assigned to these FRCs (81% and 67%, respectively) show a mean precipitation trend in decreasing and increasing direction, respectively (figure 5(a)). This could suggest that mean precipitation trends that are parallel with mean streamflow trends are associated with the 'shift' FRCs. For 'expand', most catchments similarly show an increasing trend in the standard deviation of precipitation (267 out of 376; figure 5(b)), which possibly implicates an equivalent situation, in which increasing precipitation variability may link to increasing streamflow variability. However, for 'shrink', this does not appear as common, as 287 'shrink' catchments show increasing trends and 291 show decreasing trends in the standard deviation of precipitation (figure 5(b)). Therefore, particularly in the case of 'shrink', factors beyond precipitation likely associate with flow regime change.

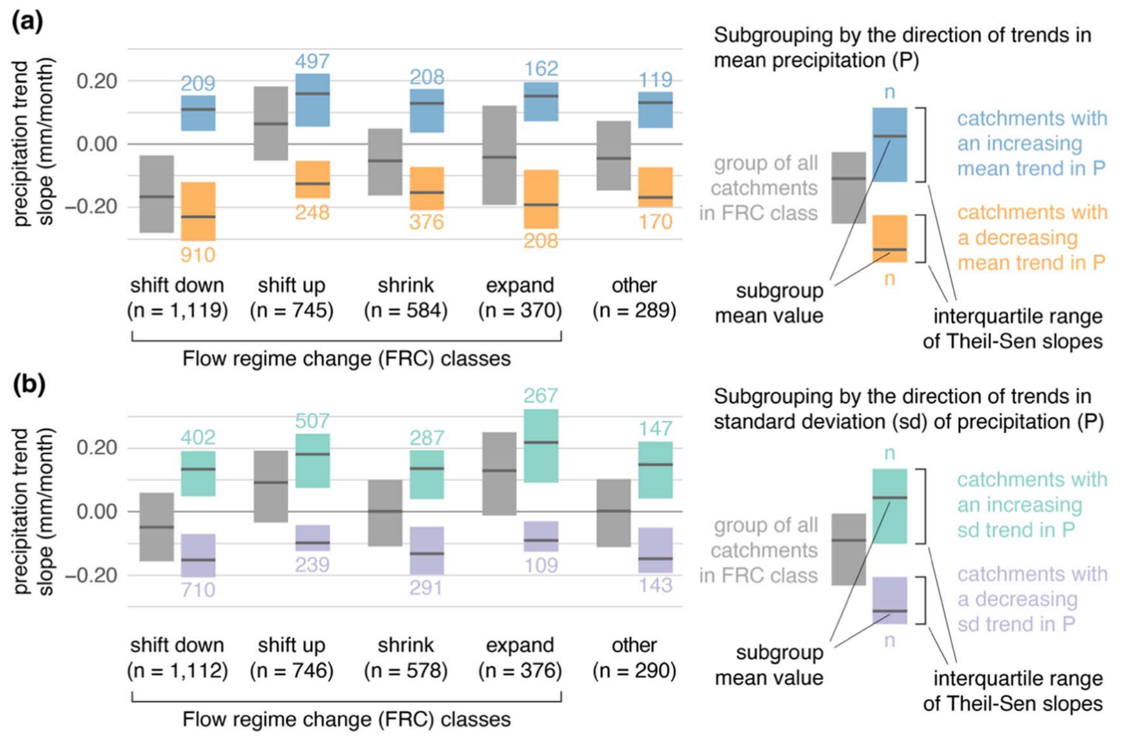

Figure 5. Grouping of catchments (n = 3,293) by linear trends in precipitation, for mean (a) and standard deviation (b). Each bar presents an interquartile range of Theil-Sen slopes in a subgroup determined by a flow regime change (FRC) class (denoted on the *x*-axis) and the direction of precipitation (P) trend for either mean or standard deviation (sd); subgroup mean is denoted with a horizontal line. Counts of catchments (n) in each subgroup are presented together with the interquartile ranges. Prior to drawing interquartile ranges and group means, outliers were removed from each FRC group, by excluding trend slopes with a magnitude more than two standard deviations away from the group mean.

Like how the 'expand' and 'shrink' FRCs are related with trends in precipitation variability (figures 5(b); 6(b)–(d)), 'expand' catchments commonly show increasing trends in the standard deviation of evapotranspiration, but for 'shrink', this correspondence is not as discernible (figures 6(e)–(g)). Additionally, notwithstanding if the FRC describes a decreasing ('shift down') or an increasing change ('shift up') in streamflow quantity, mean evapotranspiration trends are generally weaker than precipitation trends and point to the same direction (figures 6(b)–(g)). This also holds for nearly all FRC subgroups consisting of catchments in which the mean precipitation trend is opposite to the mean streamflow trend; for instance, when mean precipitation trends are increasing in 'shift down' catchments (figure S5(a)–(c)). In this sample, since precipitation trends appear stronger than evapotranspiration trends, they may be considered the more dominant factor among these two climate-related drivers.

Increasing water use trends are the strongest in the 'shift down' FRC (figures 6(h)–(j)) and additionally in the 'expand' FRC, although it should be noted that 'expand' contains the smallest number of catchments among all FRCs (table S2). On the contrary, across all catchment size groups, water use trends in the 'shrink' FRC are comparatively weak, while for the 'shift up' FRC, decreasing water use trends are the most common among the four FRCs. These decreasing trends in the 'shift up' FRC show some scale-dependence with slightly stronger decreasing water use trends when comparing large catchments to small catchments (figures 6(h)–(j)).

Increases in DOR are heavily concentrated in large catchments in the 'shift down' and 'shrink' FRCs (figures 6(k)–(m)). Although some damming occurs across all catchment size groups and FRCs—evidenced by the group means in figures 6(k)–(m) rising above zero—large catchments are by far the most affected by damming. A peculiar example of damming is seen in the 'shift down' FRC subgroup where precipitation trends are increasing; here, the mean increase in DOR reaches more than 60 percentage points and is notably larger than in any other subgroup (figure S5(i)). Though this group consists of few catchments (n = 73; table S2), this divergence may suggest cases in which large-scale flow regulation combined with increased water use (figure S5(f)) potentially offset the increasing water availability trend, eventually resulting in decreased streamflow. However, these interpretations cannot be thoroughly validated given that this analysis builds only on linear trends.

To summarise, associations between indirect drivers—precipitation and evapotranspiration—and the FRCs are strong except for 'shrink', which appears primarily associated with increasing flow regulation. The 'shift down' FRC is additionally associated with strongly increasing trends in water use, and thus related to both direct

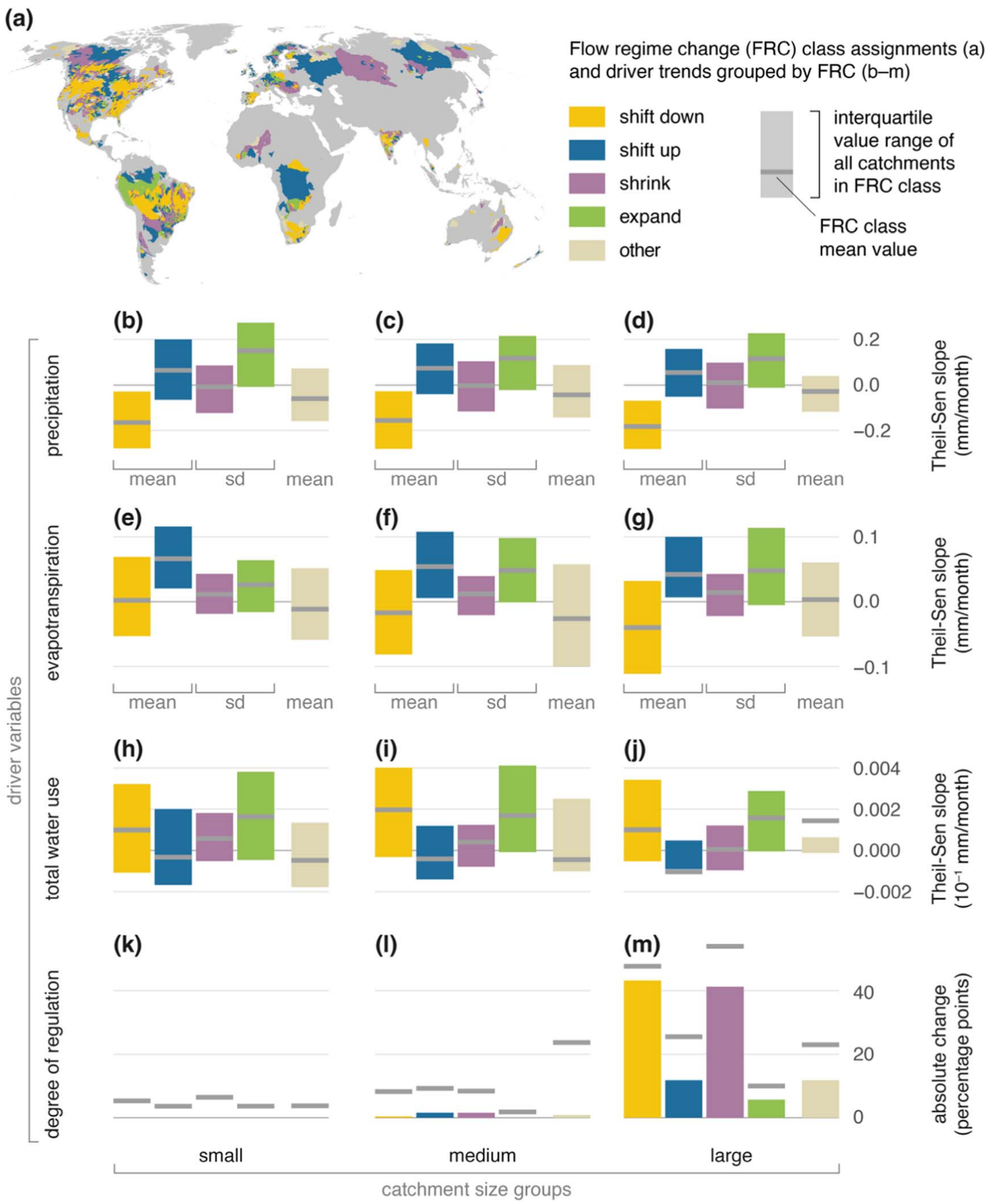

Figure 6. Flow regime change (FRC) assignments in all catchments (a) and grouping of catchments (n = 3,293) by linear trends in four driver variables: precipitation (b)–(d), evapotranspiration (e)–(g), water use (h)–(j), and degree of regulation (k)–(m). Panel (a) corresponds to figure 3. Each bar in panels (b)–(m) represents an interquartile range of Theil-Sen slopes in catchments assigned to an FRC class; group mean is denoted with a horizontal line. For precipitation and evapotranspiration, the FRC groups 'shift down', 'shift up' and 'other' display trends in mean, whereas the FRC groups 'shrink' and 'expand' display trends in standard deviation (sd). For water use, all FRC groups display trends in mean. Catchments are additionally grouped into three size groups, using a minimum catchment area of 1,000 km^2 in the small catchments group (b, e, h, k), a catchment area of 2,500 km^2 as the threshold between small and medium catchments (c, f, i, l), and a catchment area of 10,000 km^2 as the threshold between medium and large catchments (d, g, j, m). Prior to drawing interquartile ranges and group means, outliers were removed from each FRC group, by excluding trend slopes with a magnitude more than two standard deviations away from the group mean.

and indirect drivers. The 'expand' and 'shift up' FRCs likely associate the strongest with indirect drivers, while some evidence exists for associations between water use and reshaped flow regimes in the 'expand' FRC and replenished streamflow in the 'shift up' FRC. These characteristic associations also differentiate the four FRCs from the 'other' class, within which driver trends show no clear patterns (figure 6).

As the FRCs are characterised not only by streamflow trends but also by driver trends (figures (5)–(6)), the FRC map (figures 3, 6(a)) also serves as a map of possible drivers of streamflow change. The systematic association analysis supports general patterns of, for example, 'shift down' catchments often co-locating with the most intensive water use regions and 'shrink' catchments with the heaviest flow regulation (figures (3)–(4)). It should, however, be noted that these findings are based on trend correlation and co-existence rather than mechanistic representation of the water cycle. This means that the globally most frequent associations do not necessarily hold in all individual catchments, as any other trend combination beyond the globally most frequent associations between FRCs and driver trends may prevail. Without more knowledge of individual catchments, we are thus unable to assume causal relationships based on this analysis. The distinct characterisations of the four FRCs can, however, suggest broadly generalised associations between streamflow change and its drivers.

4. Discussion

The FRC assignments (figure 3) correspond well with independent estimates of streamflow change. The spatially extensive FRCs 'shift down', 'shift up' and 'shrink' largely agree with estimates of increased frequency of exceptionally dry and wet conditions, analogous to alteration in low and high flows (Porkka *et al* 2024). This is the case, especially in South and North America and Europe, where our catchment sampling density is the highest (figure S1(c)). Similarly, the FRCs coincide with recent trends in water availability in South America, but at the same time, discrepancies are seen in the southeastern United States where the 'shift down' FRC is prevalent, notwithstanding an increasing trend in water availability (Zhang *et al* 2023). This may be related to high water use (Huang *et al* 2018) and flow regulation (Grill *et al* 2019) in the region, which are both associated with the 'shift down' FRC.

In our catchment sample, precipitation trends appear stronger than evapotranspiration trends, which suggests that precipitation is the dominant driver of change in water availability. This agrees with Zhang *et al* (2023) who find similar dominance across regions that contain most of our catchments. Furthermore, climate change contributes to decreasing streamflow across South and North America, and to increasing streamflow in Central and Northern Europe (Gudmundsson *et al* 2021), which often show instances of the 'shift down' and 'shift up' FRCs, respectively. Direct drivers being especially relevant for the 'shrink' and 'shift down' FRCs and showing moderate association with the 'expand' FRC additionally agrees with Yang *et al* (2021) and Pastor *et al* (2022), who find that streamflow changes are more likely in the strong presence of direct human drivers. Thus, our key findings—based on observations—corroborate existing knowledge, which is predominantly based on modelled data at the global scale.

In agreement with comparable studies (Gudmundsson *et al* 2021, Yang *et al* 2021, Pastor *et al* 2022, Zhang *et al* 2023, Porkka *et al* 2024), we find that associations between streamflow change and its drivers vary spatially. As discussed in section 3.3, the main limitation of this study is that the globally most frequent associations do not necessarily implicate causal relationships at the scale of an individual catchment. Additionally, although we characterise the FRCs by driver trends that presumably propagate to streamflow alteration, we are unable to robustly assess the absolute contributions of the different drivers (for example, how many units does streamflow change, given a unit change in precipitation). Moreover, our study lacks explicit representation of groundwater that has a considerable impact on streamflow and is subject to manifold human pressures (Kuang *et al* 2024).

Notwithstanding the above-outlined limitations of this study, our proposed FRCs allow for shaping generic associations between streamflow change and its drivers. In future research, following recent developments of releasing observed streamflow data in structured collections (Kratzert *et al* 2023) and evolving future projections (Frieler *et al* 2024) can develop and further validate our main results across scales. Ideally with even more comprehensive catchment samples and additional drivers, future studies can increasingly add to understanding the complex dynamics of streamflow change. Advancing this knowledge is essential for evaluating the most impactful and meaningful measures for mitigating adverse impacts stemming from streamflow change.

5. Conclusion

Here, we have shown how the formation of four archetypal flow regime change (FRC) classes can provide a straightforward way to associate streamflow alteration with its drivers. Nearly all catchments (91%) in our sample are assigned to one of the four FRC classes, which also appear associated with trends in the key drivers of streamflow alteration. We find that indirect drivers, including precipitation and evapotranspiration, are strongly associated with all FRCs except for 'shrink', which describes decreasing streamflow variability and is strongly linked with increasing flow regulation. Increasing water use and decreasing trends in water availability are frequently associated with decreasing streamflow, as described by the 'shift down' FRC. The 'shift up' and 'expand' FRCs that describe increasing quantity and variability of streamflow, respectively, are weaker coupled with direct human drivers, although some moderate associations exist. These observation-based outcomes generally agree with existing knowledge grounded on model-based studies. Although an inherent drawback of our approach is that it cannot resolve causal relationships, our observation-based results provide associations that build on historically coherent hydrological systems instead of hypothetical modelling scenarios. This notably advances existing studies by highlighting the globally most frequent relations between streamflow regime alterations and their drivers, which offers action points for mitigating the adverse impacts of streamflow change. This can further support aims to decrease the manifold human pressures on the freshwater cycle.

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Data availability statement

The data that support the findings of this study are publicly available at the following DOI: 10.5281/zenodo.11102422 (Virkki *et al* 2024). The code used in producing the results shown in this study is publicly available at the following URL: https://github.com/vvirkki/flow-regime-changes.

Author contributions

V.V., R.K.S., M.S. and M.K. conceptualised the study. V.V. gathered the data, conducted the analysis, and produced the outputs shown in the study with help from R.K.S., M.S., J.L.-R. and M.K. V.V. wrote the manuscript with input from all authors.

Competing interests

Authors declare that they have no competing interests.

Supplementary materials

Supplementary materials attached to this manuscript contain figures S1–S5 and tables S1–S2.

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References

Adler R F, Gu G, Sapiano M, Wang J-J and Huffman G J 2017 Global Precipitation: Means, Variations and Trends During the Satellite Era (1979–2014) *Surv. Geophys.* **38** 679–99

Baston D 2022 Exactextractr: fast extraction from raster datasets using polygons *R package version 0.9.1* https://cran.r-project.org/web/packages/exactextractr/index.html

Best J 2019 Anthropogenic stresses on the world's big rivers *Nat. Geosci.* **12** 7–21

Chagas V B P, Chaffe P L B and Blöschl G 2022 Climate and land management accelerate the Brazilian water cycle *Nat. Commun.* **13** 5136

Dennedy-Frank P J and Gorelick S M 2019 Insights from watershed simulations around the world: Watershed service-based restoration does not significantly enhance streamflow *Glob. Environ. Change* **58** 101938

Do H X, Gudmundsson L, Leonard M and Westra S 2018 The Global Streamflow Indices and Metadata Archive (GSIM) – Part 1: The production of a daily streamflow archive and metadata *Earth Syst. Sci. Data* **10** 765–85

Frieler K *et al* 2024 Scenario setup and forcing data for impact model evaluation and impact attribution within the third round of the Inter-Sectoral Model Intercomparison Project (ISIMIP3a) *Geosci. Model Dev.* **17** 1–51

Gebrechorkos S H *et al* 2024 Global-scale evaluation of precipitation datasets for hydrological modelling *Hydrol. Earth Syst. Sci.* **28** 3099–118

Gleeson T *et al* 2020 Illuminating water cycle modifications and Earth system resilience in the Anthropocene *Water Resour. Res.* **56** e2019WR024957

GRDC 2023 BfG - The GRDC [WWW Document]. URL https://portal.grdc.bafg.de/applications/public.html?publicuser PublicUser#dataDownload/StationCatalogue (accessed November 14th, 2023)

Grill G *et al* 2019 Mapping the world's free-flowing rivers *Nature* **569** 215–21

Gudmundsson L *et al* 2021 Globally observed trends in mean and extreme river flow attributed to climate change *Science* **371** 1159–62

Gudmundsson L, Do H X, Leonard M and Westra S 2018 The Global Streamflow Indices and Metadata Archive (GSIM) – Part 2: Quality control, time-series indices and homogeneity assessment *Earth Syst. Sci. Data* **10** 787–804

Horton A J, Nygren A, Diaz-Perera M A and Kummu M 2021 Flood severity along the Usumacinta River, Mexico: Identifying the anthropogenic signature of tropical forest conversion *J. Hydrol.* **10** 100072

Huang Z *et al* 2018 Reconstruction of global gridded monthly sectoral water withdrawals for 1971–2010 and analysis of their spatiotemporal patterns *Hydrol. Earth Syst. Sci.* **22** 2117–33

Hurtado S I 2020 RobustLinearReg: Robust Linear Regressions *R package version 1.2.0* https://cran.r-project.org/web/packages/RobustLinearReg/index.html

Kåresdotter E, Destouni G, Ghajarnia N, Lammers R B and Kalantari Z 2022 Distinguishing Direct Human-Driven Effects on the Global Terrestrial Water Cycle *Earths Future* **10** e2022EF002848

Kratzert F *et al* 2023 Caravan - A global community dataset for large-sample hydrology *Sci. Data* **10** 61

Kuang X *et al* 2024 The changing nature of groundwater in the global water cycle *Science* **383** eadf0630

Levy M C, Lopes A V, Cohn A, Larsen L G and Thompson S E 2018 Land Use Change Increases Streamflow Across the Arc of Deforestation in Brazil *Geophys. Res. Lett.* **45** 3520–30

Muñoz-Sabater J *et al* 2021 ERA5-Land: a state-of-the-art global reanalysis dataset for land applications *Earth Syst. Sci. Data* **13** 4349–83

Nilsson C, Reidy C A, Dynesius M and Revenga C 2005 Fragmentation and Flow Regulation of the World's Large River Systems *Science* **308** 405–8

Pastor A V, Biemans H, Franssen W, Gerten D, Hoff H, Ludwig F and Kabat P 2022 Understanding the transgression of global and regional freshwater planetary boundaries *Philos. Trans. R. Soc. Math. Phys. Eng. Sci.* **380** 20210294

Poff N L, Olden J D, Merritt D M and Pepin D M 2007 Homogenization of regional river dynamics by dams and global biodiversity implications *Proc. Natl Acad. Sci.* **104** 5732–7

Porkka M *et al* 2024 Notable shifts beyond pre-industrial streamflow and soil moisture conditions transgress the planetary boundary for freshwater change *Nat. Water* **2** 262–73

Richardson K *et al* 2023 Earth beyond six of nine planetary boundaries *Sci. Adv.* **9** eadh2458

Telteu C-E *et al* 2021 Understanding each other's models: an introduction and a standard representation of 16 global water models to support intercomparison, improvement, and communication *Geosci. Model Dev.* **14** 3843–78

Theeuwen J J E, Staal A, Tuinenburg O A, Hamelers B V M and Dekker S C 2023 Local moisture recycling across the globe *Hydrol. Earth Syst. Sci.* **27** 1457–76

Veldkamp T I E *et al* 2018 Human impact parameterizations in global hydrological models improve estimates of monthly discharges and hydrological extremes: a multi-model validation study *Environ. Res. Lett.* **13** 055008

Virkki V *et al* 2022 Globally widespread and increasing violations of environmental flow envelopes *Hydrol. Earth Syst. Sci.* **26** 3315–36

Virkki V, Sahu R K, Smilovic M, Láng-Ritter J, Porkka M and Kummu M 2024 Data for "Archetypal flow regime change classes and their associations with anthropogenic drivers of global streamflow alterations" (v1.0.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.11102422

Wada Y and Bierkens M F P 2014 Sustainability of global water use: past reconstruction and future projections *Environ. Res. Lett.* **9** 104003

Wang J *et al* 2022 GeoDAR: georeferenced global dams and reservoirs dataset for bridging attributes and geolocations *Earth Syst. Sci. Data* **14** 1869–99

Wang-Erlandsson L, Fetzer I, Keys P W, van der Ent R J, Savenije H H G and Gordon L J 2018 Remote land use impacts on river flows through atmospheric teleconnections *Hydrol. Earth Syst. Sci.* **22** 4311–28

Yang Y, Roderick M L, Yang D, Wang Z, Ruan F, McVicar T R, Zhang S and Beck H E 2021 Streamflow stationarity in a changing world *Environ. Res. Lett.* **16** 064096

Zhang Y *et al* 2023 Southern Hemisphere dominates recent decline in global water availability *Science* **382** 579–84