Snowmelt Influence on Northern Hemisphere River Discharge - The Potential of Causal Inference for Assessing Long-Term Trends

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Abstract. Snowmelt is a vital contributor to river discharge across the Northern Hemisphere, supplying freshwater to over 1.5 billion people and supporting key economic sectors such as agriculture and hydropower. However, climate change has led to a decline in snow water equivalent (SWE) on almost the entire Northern Hemisphere, reducing snow-based water availability. Despite the importance of snowmelt and the pressure imposed by climate change, no large-scale studies have examined the connection ~~of~~ between snowmelt dynamics and river discharge beyond statistical measures, which fail to capture the complexity of hydrological regimes. To address this gap, we ~~perform causal discovery using PCMCI~~apply PCMCI+, a method that adapts the PC algorithm proposed by Peter Spirtes and Clark Glymour to the ~~time series setting, to obtain qualitative causal structure~~ time-series setting. We use it to derive qualitative causal structures across 119 basins from 1980 to 2022 and then quantify the causal effects using ~~causal effect estimation with~~ a 20-year moving window and a ~~random forest~~ random-forest estimator. Our results show that the role of snowmelt in streamflow generation is changing. In various basins where the method allows for trend detection, the ~~ratio of the~~ causal effect of snowmelt on river discharge~~to the mean of the river discharge~~, normalized by mean river discharge, is increasing despite declining SWE. This suggests that ~~as precipitation patterns shift and intra-annual variability increases, snowmelt may become more important for streamflow generation~~ the growing causal role of snowmelt is primarily driven by increasing anomalies in snowmelt itself, rather than by a strengthening coupling between snowmelt and discharge, in certain basins despite a generally declining SWE. While regional differences emerge, causal effects do not consistently correlate with geographical factors such as latitude or basin characteristics. Analyses in six basins that serve as illustrative examples ~~,~~indicate that changes in seasonal hydrology, particularly the timing and distribution of precipitation, influence the relative role snowmelt plays for river discharge. These findings ~~highlight the power~~ demonstrate the potential of causal inference ~~over~~ as a complement to conventional statistical measures in ~~enhancing~~ the analysis of large-scale snow hydrological regimes~~by adding depth to existing approaches~~.

. TEXT

1 Introduction

1.1 Snow as a river flow driver

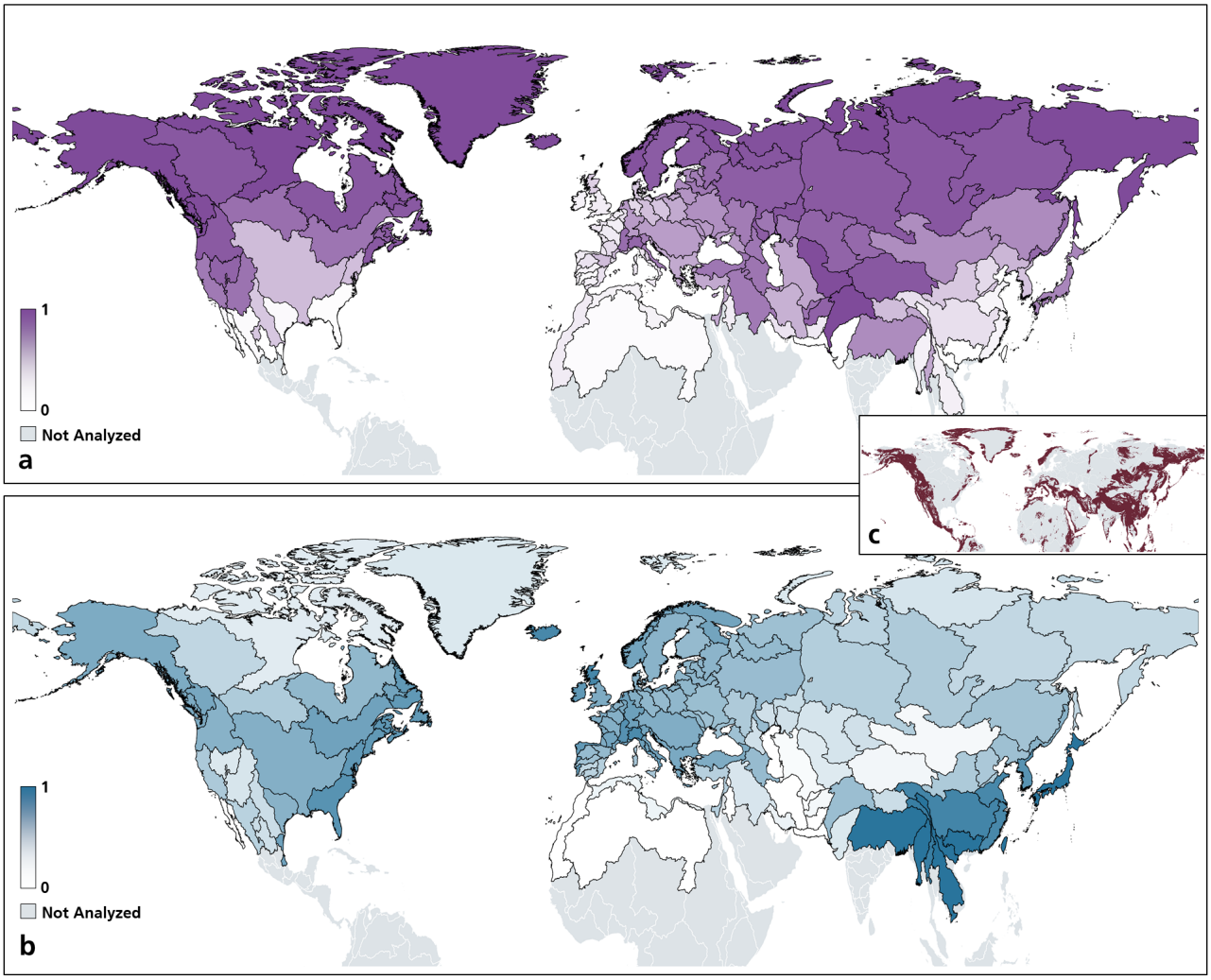
In various regions of the world, especially ~~on~~ in the Northern Hemisphere, snowmelt is the dominant streamflow driver and serves as the primary freshwater source for over 1.5 billion people worldwide and thus their economic, societal and environmental livelihoods. (Barnett et al., 2005; UN DESA, 2022). Unlike rain, snow not only serves as a water resource but also as a storage mechanism. Snow accumulates mainly during winter and contributes to streamflow during the ablation phase, entering the stream through overland flow, subsurface flow, or intermediate storage such as glaciers and groundwater (DeWalle and Rango, 2008; Viviroli et al., 2007; Tague and Grant, 2009). Downstream, the water is subsequently used for various purposes.

~~*H~~However, the reliability of snow-dominated rivers as a freshwater resource is deteriorating due to changes induced by ~~an~~thropogenic ~~climate change~~ global warming in the upstream snowpacks (Fig. **??**, label 11,

Downstream, several systems crucial for human livelihood are increasingly subjected to the impacts of these changes, as schematically shown in figure **??**. Agriculture in snow-dominated regions, for example, is closely tied to the availability of water from snowmelt and can therefore suffer reduced harvests and crop failure (Fig. **??**, label 7, ~~Qin et al. (2022); Huning and AghaKoucha~~ Qin et al. 2022; Huning and AghaKouchak 2020). Other economic sectors such as hydropower (Fig. **??**, label 3, ~~Soomro et al. (2024)~~ Soomro et al. 2024), inland cargo shipping (Fig. **??**, label 6, ~~Schweighofer (2014); Bedoya-Maya et al. (2024)~~Schweighofer 2014; Bedoya-), and tourism (Fig. **??**, label 1, ~~François et al. (2023)~~François et al. 2023), which in some regions are reliant on consistent snowpacks, are also affected. Additionally the changing snowpack intensifies the demand on civil infrastructure regarding heightened flood risk (Fig. **??**, label 4, ~~(Zhou et al., 2022)~~Zhou et al. 2022), or snow avalanches (Fig. **??**, label 2, ~~Eckert et al. (2024)~~ Eckert et al. 2024). Communities, especially indigenous peoples, who are heavily affected by these developments also experience changes in their cultures and languages (Fig. **??**, label 10) and are sometimes also forced to migrate to safer places (Fig. **??**, label 5, ~~(Ford et al., 2021; Reyes-García et al., 2024)~~Ford et al. 2021; Reyes-García et al. 2024). Finally, the effects of changing global snow cover extend beyond human systems, influencing flora and fauna through numerous ecological processes (Fig. **??**, label 9~~(Inouye, 2022; Slatyer et al., 2024; Wenzl et al., 2024)~~, Inouye 2022; Slatyer et al. 2024; Wenzl et al. 2024).

~~A brief overview of the role of snow on the hydrological regime in various basins is provided in figure 2 by displaying~~ Figure 2 shows the ratio of ~~Snow Water Equivalent (SWE)~~ snowmelt to total precipitation in 119 river basins. This ratio serves as a measure of snow dominance, highlighting regions where and to what extent snow contributes to streamflow generation. Generally the snow dominance increases ~~by~~ with latitude, and around major mountain ranges (compare figure 2 right insert (c)). Figure 2b shows the normalized average of total precipitation, as an indication for the general hydroclimatology in the

analyzed basins. This provides context for interpreting the ~~SWE-to-precipitation~~ snowmelt-to-precipitation ratio, as basins with lower total precipitation tend to show relatively higher ratios.



~~Top: Normalized average ratio between snowmelt and total precipitation in the analyzed river basins for 1980-2022 (Data: Snow_CCI (Luojus et al., 2024), ERA_5 (Muñoz Sabater, 2019)), Bottom: Normalized average monthly total precipitation (1980-2022) in the analyzed river basins (Data: Era_5 (Muñoz Sabater, 2019)). Middle right (c): Mountainous areas of the Northern Hemisphere (Data: GMBA Inventory v2.0 (Snethlage et al., 2022)).~~

Figure 2. Top: Normalized average ratio between snowmelt and total precipitation in the analyzed river basins for 1980-2022 (Data: ERA_5 (Muñoz Sabater, 2019)), Bottom: Normalized average monthly total precipitation (1980-2022) in the analyzed river basins (Data: Era_5 (Muñoz Sabater, 2019)). Middle right (c): Mountainous areas of the Northern Hemisphere (Data: GMBA Inventory v2.0 (Snethlage et al., 2022)).

Despite this extensive research on Northern Hemisphere snow water equivalent (SWE), since 2000, only a minority of large-scale studies ~~connected SWE with~~ have connected SWE to broader contexts in their design or data use ~~since the year 2000~~ (Schilling et al., 2024; Gordon et al., 2022). When such links were made, they focused almost exclusively on water availability, including terrestrial water storage (TWS), river discharge, or droughts, with only few studies extending beyond these ~~themes. There are~~ topics. There were two studies that linkedSWE to TWS on a global scale (Zhang et al., 2019; Tangdamrongsub et al., 2021) and one hemispherical analysis (Girotto et al., 2021)~~, but no studies linking SWE to river discharge on a hemispherical or global scale (Schilling et al., 2024; Gordon et al., 2022). The only~~ . Furthermore Han et al. (2024) connected SWE to streamflow on a hemispheric scale linking snow fraction to streamflow seasonality across 3,049 catchments in the Northern Hemisphere. However, this study addresses the timing rather than the magnitude of snowmelt's contribution to discharge. Other studies conducted beyond a national or basin scale linking river discharge to SWE were two Pan-Arctic studies (Rawlins et al., 2007; Biancamaria et al., 2011), and when the scope is extended to snow cover research, only one Arctic study linking snow cover to discharge, that relies on a precipitation model rather than remote sensing data (Park et al., 2024).

Generally three types of approaches are used to quantify the SWE contribution to river discharge. Firstly, most SWE–discharge ~~investigations~~ studies employ statistical measures of association, mostly correlations or regression approaches, which can only incorporate additional drivers or temporal lags to a limited extent (e.g.Xu et al. (2009); Tong et al. (2010); Biancamaria et al. (2011); Wang et al. (2017); Kumar et al. (2019)). Secondly, ratio-based approaches, such as the snow dominance ratio used globally by Barnett et al. (2005) and Gottlieb and Mankin (2024) or regionally by Li et al. (2017), assume total precipitation equals discharge and likewise do not explicitly address storage, evaporation or time lags. Finally, the analysis of stable oxygen isotopes can also distinguish snowmelt contributions in streamflow (Craig, 1961), but its reliance on intensive field sampling limits studies to small catchments (López-Moreno et al., 2023; Lucianetti et al., 2020; Beria et al., 2018).

In sum, no ~~hemispherical-scale~~ hemispherical scale study currently quantifies snow~~'~~'s role in river discharge composition ~~. Existing large-scale research relies on methods that do not fully explore multivariate and temporal dynamics, underscoring~~ using multivariate, time-lagged methods (Schilling et al., 2024; Gordon et al., 2022). Also the streamflow seasonality analysis by Han et al. (2024) addresses timing rather than magnitude, and relies on correlational rather than causal methods. This underscores the need for analyses that ~~extend beyond statistical associations and~~ incorporate time-lagged, storage-sensitive mechanisms.

1.2 Background on Causal Inference in Environmental Science

Causal inference methods are driven by the question: "What effect does a certain trigger variable X have on a target variable Y?" An early attempt to address this question was made by Granger (1969), who introduced the concept of using the unique predictive power of X to identify causal relationships in time series. Later, Spirtes (1996) enabled the analysis of causal relationships along a causal graph. Furthermore, Pearlian approaches expanded this framework to multivariate and ~~lag specific~~

lag-specific contexts, allowing tests of conditional independence across time as well as the quantification of the effect that an intervention *X'* has on *Y* (Runge et al., 2012; Pearl, 2000).

In environmental applications, such causal effects are often interpreted in terms of the contribution of individual processes or variables to a system response. In the context of snow hydrology, this naturally raises the question of how snowmelt contributes to river discharge and how this contribution varies across space and time. In this study, we apply a recently developed causal inference method, causal effect discovery, based on ~~the~~ Peter Clark Momentary Conditional Independence ~~(PCMCI) framework developed by Runge et al. (2019), in~~ Plus (PCMCI+) (Runge, 2020), an extension of the original PCMCI algorithm (Runge et al., 2019) described in more detail in Section 2.5.1, in combination with the causal effect estimation approach introduced by Runge (2021). Throughout this paper, we use PCMCI to refer to the general family of algorithms and PCMCI+ when referring specifically to the method applied in this study.

While initially developed for economic research (Granger, 1969), causal inference methods have recently gained traction in environmental and Earth observation (EO) studies. Granger causation has been applied in ecological research (e.g. ~~Philippon et al. (2005); C~~ Philippon et al. 2005; Cicuendez et al. 2015; Zhu and Meng 2015) as well as in broader environmental and climate related studies (e.g. ~~Beyers (1998); Capua et al. (2020); Pérez Valentín and Müller (2020)~~Beyers 1998; Capua et al. 2020; Pérez Valentín and Mül). With the development of PCMCI, the scope of causal inference applications in EO studies has further expanded, enabling multivariate and lag aware analyses of complex environmental systems (e.g. ~~Uereyen et al. (2022); Sogno et al. (2024); Karmouche et al. (2~~ Uereyen et al. 2022; Sogno et al. 2024; Karmouche et al. 2023).

Snow-related variables have been incorporated into multivariate environmental systems in a number of studies using causal inference. However, in most of these studies, snow was not the primary focus, but rather one of several variables considered in their causal networks, often without explicitly quantifying its contribution to river discharge or water availability (e.g. ~~Kretschmer et al. (2016); Uereyen et al. (2022); Kolluru et al. (2024); Yuan et al. (2024)~~Kretschmer et al. 2016; Uereyen et al. 2022; Kollu). Causal studies with a hydrological focus have instead concentrated on specific phenomena such as floods (Sun et al., 2024; Kashyap and Behera, 2024), rain on snow events (Koya et al., 2024), or groundwater dynamics (Zhang et al., 2019). A recent study by Kim et al. (2025) examined the influence of sea surface temperature variability on North American snow resources, but did not explicitly link snow dynamics to downstream hydrological responses. ~~Therefore~~To our knowledge, to date, no large scale causal analysis has specifically examined the contribution of snowmelt or snow water equivalent to river discharge across extended spatial and temporal scales.

Given the demonstrated applicability of PCMCI to environmental time series, it can be considered a suitable framework for addressing this research gap.

This study thus presents a hemispherical scale causal inference analysis of snow hydrology, targeting the contribution of snowmelt and rain to river discharge. The analysis incorporates variables beyond ~~SWE and~~ snowmelt and river discharge, including rain, soil moisture, evapotranspiration, glacier runoff, baseflow flux, and temperature, while accounting for time lags of up to six months. This is complemented by a descriptive trend analysis of snow water equivalent (SWE) and related variables. The differentiation between snowmelt and SWE across the two analyses reflects their different purposes: the causal

inference requires snowmelt as an input to resolve its seasonal contribution to river discharge, whereas the trend analysis uses SWE directly, to remain comparable with existing SWE studies.

The choice of a specific causal inference method should reflect the structural properties of the system under study rather than be made by default. A range of approaches exist for identifying causal relationships in multivariate, time-evolving data, including information-theoretic methods such as the Liang-Kleeman information flow (LKIF; Liang and Kleeman 2005) and constraint-based graphical methods such as PCMCI and PCMCI+ (Runge et al., 2019, 2023). Since our system comprises eight interacting hydrological and atmospheric variables observed across multiple time lags, a method needs to be able to condition on the full set of common drivers and mediators. Simpler bivariate approaches cannot adequately rule out indirect or confounded links under such conditions. Docquier et al. (2024) systematically benchmarked PCMCI against LKIF across synthetic systems of increasing complexity and a real-world case study and found that, while both methods outperform classical correlation-based analysis, PCMCI performs comparatively better as the number of variables in the system increases. While not a direct validation of our specific setup, this supports our choice to use PCMCI+ as an appropriate framework for the multivariate, hemispherical scale snowmelt-discharge system examined here.

2 Data and Methods

The workflow in this study can be distinguished into three main phases: Downloading and Preprocessing, Statistical Metrics and Trend Calculation, and Causal Inference. In the following section we describe these working phases as well as the utilized data and the study area. A schematic overview of the used data, as well as the workflow is shown in 3. There is no validation section provided here, as no independent data are available that are both spatially and temporally suitable for the scale of this study. All utilized data, as well as the corresponding updates by the providing entities, ~~was~~ were validated by the developers and published in peer-reviewed studies (cited in the corresponding sections), and ~~is~~ are thereby meeting the qualitative requirements of the analysis at hand.

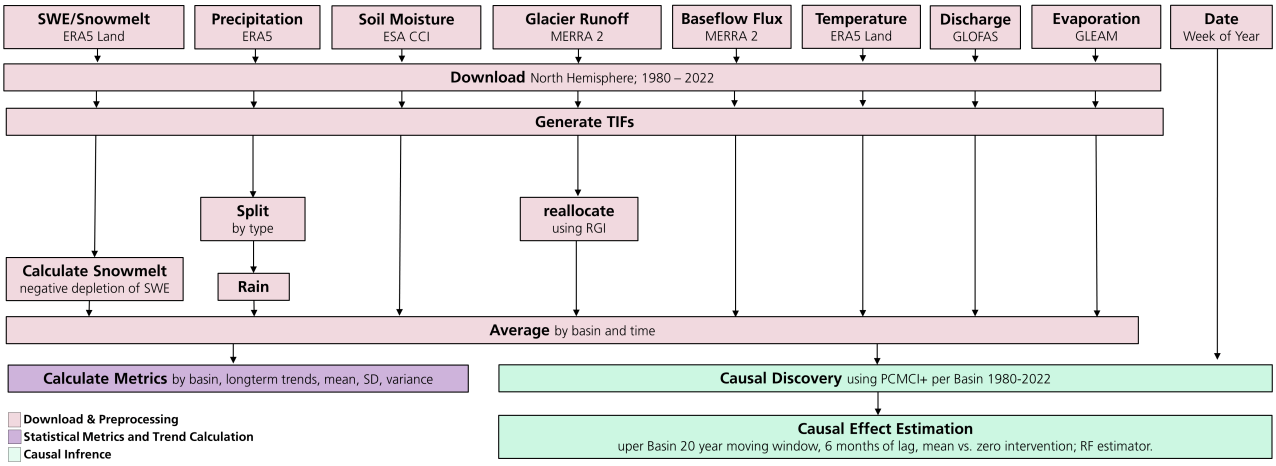


Figure 3. Schematic illustration of the applied data and workflow. Data abbreviations explained in table 1. Randolph Glacier Inventory (RGI; RGI 7.0 Consortium 2023) used to reallocate Glacier data if needed.

2.1 Studied Basins and Period

For the delineation of the hydrological basins we use the "Major Hydrological Basins of the World" dataset from the Food and Agriculture Organization of the United Nations (FAO, 2011). The dataset defines basins as top-level drainage areas bounded by topographic divides, within which all surface water flows toward a common outlet such as a river, lake, or ocean (FAO, 2011). Based on the ~~Climate Change Initiative Data by the European Space Agency (ESA) for Snow (SnowCCI), version 3.1 (Luojus et al., 2024) and~~ ECWMF reanalysis land (ERA 5 Land~~/ ERA 5) (Muñoz Sabater, 2019)~~ ; Muñoz Sabater 2019) SWE datasets, we determine the number of years each basin had snow coverage between 1980 and 2022.

We select basins that have snow coverage for at least 30 ~~years during this time period~~of these 43 years, yielding 119 basins for examination. We focus on the Northern Hemisphere because, although there are snow-dominated regions in the Southern Hemisphere, the majority of the world's SWE, snow-dominated rivers, and thus the human populations affected by the described effects in the introduction, are found in the Northern Hemisphere (Barnett et al., 2005; UN DESA, 2022; Tangdamrongsub et al., 2021).

We choose the period from 1980 to 2022 because ~~of the availability of~~ 1980 marks the beginning of consistent passive microwave satellite coverage, on which the employed soil moisture dataset ~~, which is based on passive microwave satellite data~~relies. The extent of the analyzed basins can be seen in the figure 2.

2.2 Data

~~Table 1 provides an overview of the datasets used and their sources.~~ Generally, spatial and temporal considerations guide the data selection. When multiple comparable datasets were available, we select the dataset based on practical handling aspects~~(e.g. evapotranspiration datasets). For rain and~~ .

For temperature we use ~~the ERA-5 and ERA-5 Land data respectively~~ERA5-Land, provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) and ~~which is~~ available in the Copernicus Climate Data Store (CDS). ERA5-Land is likewise used as the SWE data source, as it was identified as the top-performing product for Northern Hemisphere SWE across a comprehensive range of evaluation metrics in the SnowPEx+ intercomparison by Mudryk et al. (2025), supporting its use as the primary dataset for a hemispheric-scale study. For rain we instead use the coarser-resolution ERA5 product, since ERA5-Land does not provide a precipitation type variable, which is required to separate liquid from solid precipitation (see Section 2.3.2). River discharge data ~~is~~ were provided by the Global Flood Awareness System (GloFAS), and the soil moisture (SM) data by the European Space Agency (ESA) Climate Change Initiative (CCI), both datasets are also obtained from the CDS. The baseflow flux, which serves as a proxy for groundwater runoff, and the glacier runoff data come from the Modern-Era Retrospective analysis for Research and Applications Version 2 (MERRA 2) provided by the Global Modeling and Assimilation Office (GAMO) of the National Aeronautics and Space Administration (NASA). ~~.~~Finally, for evapotranspiration we use the evapotranspiration variable from the Global Land Evaporation Amsterdam Model (GLEAM) version 4.1, which is maintained by the University of ~~Gent.~~ Ghent. For this study, we exclude open-water evaporation from the evapotranspiration variable, since it operates directly at the river surface rather than through terrestrial pathways, and exclude snow sublimation, as its inclusion would contradict the snowmelt definition used here (Section 2.3.1). Within this setup, evapotranspiration is expected to influence river discharge indirectly through soil moisture depletion, which is included as a mediating variable in the causal graph (see Appendix A). Table 1 provides a complete overview of the datasets used and their sources.

2.3 Preprocessing

We download all data in the provided temporal resolution and average by calculating the biweekly mean. Spatially we average the data by basin, using a proportional approach to avoid values being attributed to multiple basins. Therefore we overlay the variable data, which are all provided as raster data over the vector geometries of the basins. For all pixels that touch more than one basin, we calculate the share of each basin, and attribute the value accordingly. The individual preprocessing steps applied per variable are described in the following subsections. Note that stationarity is a requirement for PCMCI+ and therefore detrending and a seasonal decomposition of the time series ~~is~~ are suggested by Runge et al. (2023). Our objective, however, is to preserve possible long-term trends in the causal factors. We therefore do not detrend the data or subtract a fixed seasonal climatology. Instead, we incorporate a deterministic seasonality variable to allow causal relationships to vary within seasons and repeat the analysis using a sliding window to assess the impact of climate change. This avoids filtering aggregated seasonality and accounts for the potential shift of seasonal patterns under climate change. This approach is described in more detail in section 2.5.1.

2.3.1 SWE / Snowmelt

Since the causal inference focuses exclusively on the snowpack's contribution to river discharge, thus the ablation phase, we use snowmelt as an input variable for the causal inference rather than SWE. Therefore we convert SWE into snowmelt, defined as the depletion of the SWE between successive time steps (Musselman et al., 2017; Wu et al., 2022). For each pixel we

Table 1. Data used for the analysis with the corresponding sources. Biweekly averages were used for all datasets.

Variable	Source	Unit	Res.	Data Type	Last Accessed	Remarks
Basin Outlines	FAO Major Hydrological Basins (FAO, 2011)	-	–	Vectorized Basin Outlines	Jul. 2025	-
Rain	ERA 5; ECWMF (CDF) (Hersbach et al., 2023)	m	0.25°	Reanalysis	Dec. 2025	Liquid precipitation classification using the precipitation type variable of ERA 5.
Temperature	ERA 5 Land; ECWMF (CDF) (Muñoz Sabater, 2019)	K	0.1°	Reanalysis	Nov. 2025	2m temperature.
SWE/Snowmelt	~~Snow CCI v3.1 (Luojus et al., 2024);~~ ERA 5 Land; ECWMF (CDF) (Muñoz Sabater, 2019)	~~mm;~~ m	~~PMW & in-situ;~~ 0.1°	Reanalysis	~~ERA 5 used to fill data gaps in SnowCCI data. Snowmelt defined as the negative depletion of SWE~~Jun. 2026	SWE used directly for descriptive trend analysis (Section 2.4); converted to snowmelt, defined as its negative depletion between time steps, for causal analyses (Section 2.3.1).
River Discharge	GloFAS (Grimaldi et al., 2022)	m^3/s	0.05°	Reanalysis	Nov. 2025	-
Soil Moisture	ESA CCI (Dorigo et al., 2019)	m^3/m^3	0.25°	Passive & Active MW	Nov. 2025	No data days interpolated.
Baseflow Flux	MERRA-2 (GMAO, 2015a)	m^3/s	0.5° × 0.625°	Reanalysis	Nov. 2025	-
Glacier Runoff	MERRA-2 (GMAO, 2015b)	m^3/s	0.5° × 0.625°	Reanalysis	Nov. 2025	-
Evapotranspiration	GLEAM v4.1 (Miralles et al., 2024)	mm	0.1°	Model	Dec. 2025	-

calculate the difference in SWE between consecutive time steps and sum all negative changes as absolute values to quantify total snowmelt. This conversion is applied exclusively for the causal inference framework (Section 2.5). The descriptive trend analysis of variables (Section 2.4) uses SWE directly, without conversion to snowmelt.

2.3.2 Precipitation / Rain

~~To avoid redundant inclusion of the contribution of snow~~

To isolate the liquid fraction of precipitation and thereby avoid conflating precipitation-driven and snowmelt-driven contributions to river discharge, we ~~subtract it from the ERA5 total precipitation data to generate an intermediary~~ derive a liquid precipitation

dataset, referred to as *rain* throughout this paper~~. We distinguish between frozen and liquid precipitation ,~~, directly from ERA5 total precipitation. We use ERA5 rather than ERA5-Land for this purpose, since ERA5-Land does not provide a precipitation type variable, which is required to separate liquid from solid precipitation. This is done using the precipitation type ~~from~~ variable provided by the CDS (Hersbach et al., 2023), ~~on an hourly basis, and only perform the biweekly averaging on the resulting liquid preciptation dataset *rain*. The rain data are finally averaged biweekly .~~ which classifies each hourly precipitation value as liquid or solid, of which we only retain the liquid fraction. This classification is applied on an hourly basis before biweekly averaging. Note that *rain* is derived independently of snowmelt, which is calculated separately from the depletion of snow water equivalent (SWE) as described in Section 2.3.1, rather than by subtracting snow-related quantities from total precipitation.

2.3.3 Glacier Runoff

The MERRA-2 data, used for the glacier runoff variable, has a resolution of 0.625° × 0.5° (GMAO, 2015b). This resolution occasionally results in pixels with runoff values touching basins that have no glaciers. In our proportional approach for attributing the pixel values to the basins, glacier runoff would thus be falsely included in the analysis of these basins, if not addressed. To counteract this issue, we identify glacier locations using the Randolph Glacier Inventory (RGI) v7.0 (RGI 7.0 Consortium, 2023). We use spatial overlap analysis to reveal basins which contain no glaciers but have runoff attributed to them and manually reallocate their glacier runoff to reflect hydrological conditions as accurately as possible.

2.4 Statistical Metrics and Trend Calculation

For all data-based variables (see Table 1), we compute~~d~~a range of statistical measures (mean, median, variance, and standard deviation [StDev]) for each basin to characterize the data distribution and behavior. Note that this trend analysis uses SWE directly, in contrast to the causal inference framework described in Section 2.5, which uses snowmelt derived from SWE as described in Section 2.3.1. Additionally, we apply a Theil-Sen estimator (Sen, 1968) to each variable and basin to estimate trends while minimizing outlier influence. Since the Theil-Sen estimator lacks an inherent significance measure, we combine it with a Mann-Kendall test to evaluate trend significance. We ~~also normalize the~~ normalize the resulting Theil-Sen ~~slope by the basinaverage per variable~~ slopes in two steps. First, for each basin and variable, the slope is normalized by that basin's own mean of the variable over the full 1980-2022 period, yielding a unitless relative trend that is comparable across variables with different magnitudes and units. Second, for visualization purposes, these basin-normalized trends are additionally normalized across all basins per variable by the maximum absolute value, preserving sign, such that the basin with the most extreme trend is mapped to ± 1. These statistical analyses and trend estimations provide a comprehensive understanding of the data across the study region and support a detailed discussion of causal effects and trends across basins.

2.5 Causal Inference

Our causal inference framework (schematic overview in figure 5) consists of two phases~~;~~ : causal discovery and causal effect estimation. The causal discovery phase constrains the causal graph based on a series of unconditional and conditional independence tests. The causal graph describes the relationships between the different variables over the defined time lags. The causal effect estimation phase uses the causal graph to determine the effect that an intervention on a trigger variable has on a target variable (Runge et al., 2023; Pearl, 2000). ~~A schematic overview of the causal inference framework as well as its utilization in this study is displayed in figure 5.~~

We run PCMCI+ once per basin over the entire study period to detect ~~basin specific~~ basin-specific relationships between the examined variables. This is possible because we assume that basic hydrological principles remain unchanged for the entire study period.

Following causal discovery we perform a series of causal effect estimations on 23 subperiods of 20 years (1980-1999, 1981-2000, ..., 2003-2022) for each basin. ~~This~~ In addition to enabling the detection of long-term change in effect size, this moving window design ~~allows us to depict changes in the effect size within the examined time period~~restricts each individual estimation to a shorter temporal period, reducing the influence of long-term trends on the causal effect estimates within any given window. We average the values from the subperiods per year resulting in a 43-year yearly time series of causal effects per basin and trigger variable. The effect estimation is run for the 119 basins mentioned in section 2.1 and for the trigger variables snowmelt and rain, as these variables may be regarded as primary drivers within our assumed system, which subsequently influence all other hydrological variables (DeWalle and Rango, 2008). Our framework addresses non-stationarity without modifying the data in two ways: (1) we address seasonal non-stationarity through the inclusion of a calendar week index as an explicit variable in the causal graph, which relaxes the stationarity assumption to year-to-year rather than across the full record, and (2) we address long-term trends through the rolling window approach, which restricts each estimation to a 20-year period where the trend is small enough to be ignored. We confirmed this using Theil-Sen and Mann-Kendall trend analysis across all 20-year moving windows. Even for variables with a significant long-term trend over the full 43-year record, the vast majority of individual 20-year windows showed no statistically significant trend, and if significant trends were detected, they were confined to specific sub-periods rather than present throughout the record. Since non-stationarity is addressed within the method rather than by preprocessing the data, formal stationarity tests are not applicable in this context.

To confirm the basic functionality of the method, we carry out a set of ~~sanity checks . We introduce modifications to selected variables (snow or rain) and examine whether the detected effects (on river discharge) changed~~ plausibility checks using artificially modified input data. We apply two mirrored scenarios to the input time series: in the first, a compounding scaling factor artificially increases the snowmelt signal while simultaneously decreasing the rainfall signal. In the second, the opposite scaling is applied. We repeat this check for both trigger variables across a range of basins and consistently find the detected causal effects to respond in the expected qualitative ~~manner. These checks serve as sanity tests rather than a sensitivity analysis.~~ direction. The results for the Danube basin as representative example show the functionality of the method (fig. 4). The

following subsections further describe our application and parametrization of the two causal inference phases on the snowmelt river discharge relationship.

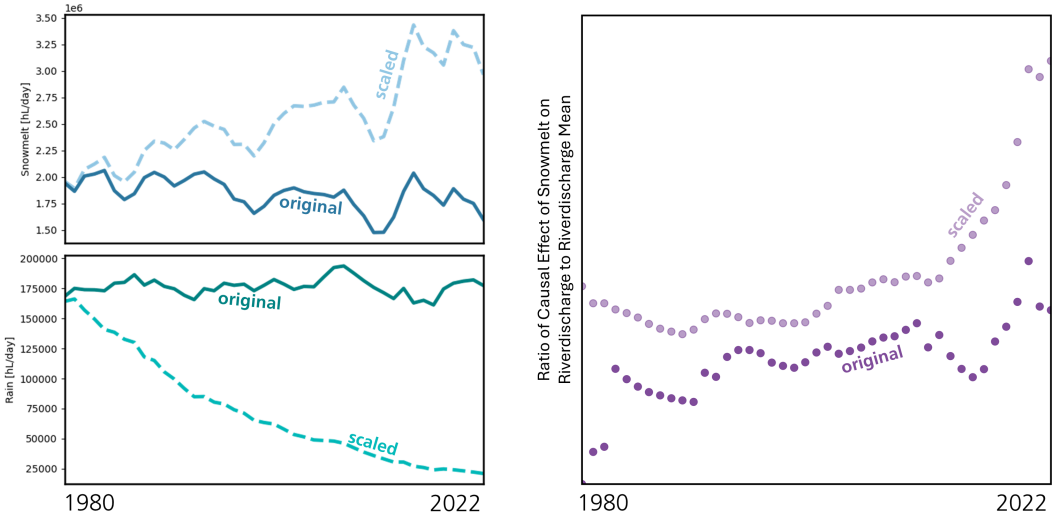
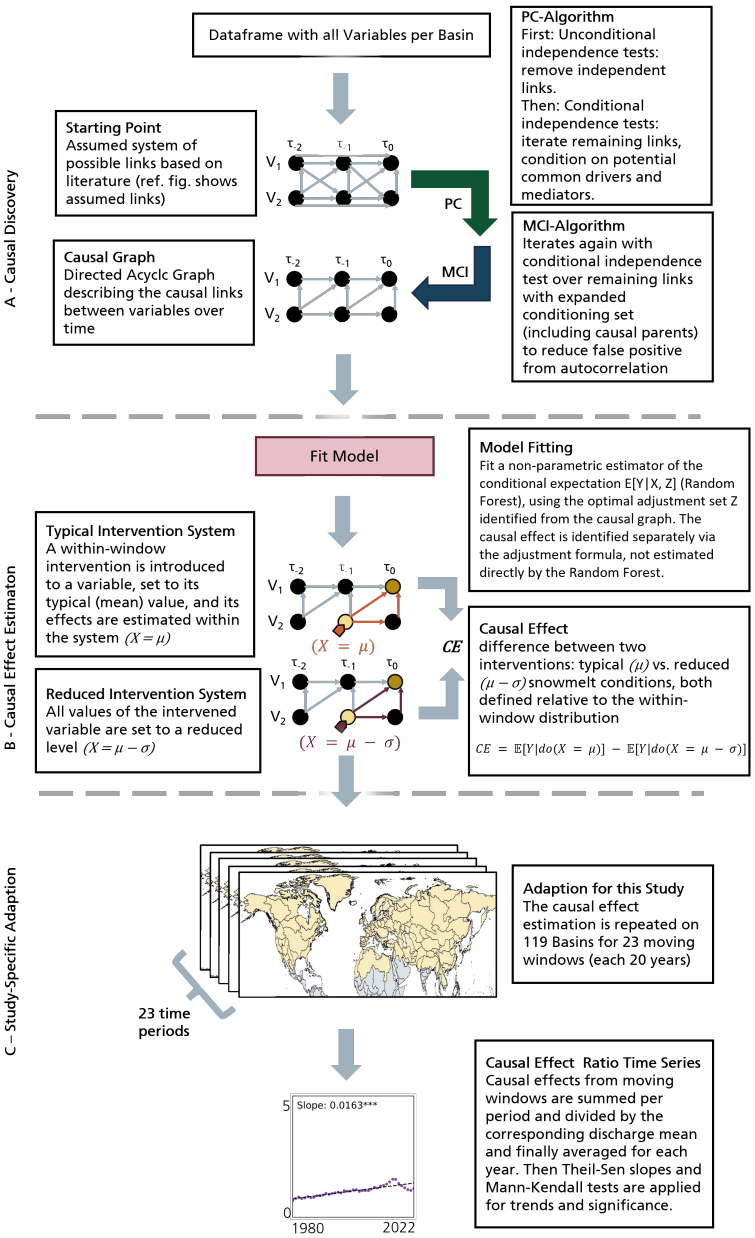


Figure 4. Plausibility check results for the Danube basin, shown here as a representative example, using artificially modified snowmelt and rain input signals. The causal effect of the amplified trigger variable increases and the causal effect of the attenuated trigger variable decreases under each scenario, confirming that the detected causal effects respond in the expected qualitative direction to changes in the underlying input signals.



~~Schematic illustration of the causal inference framework applied in this study. A) Causal Discovery; PC and MCI algorithms examine statistical conditional independences of relationships between variables, which in turn are used to draw the causal graph. B) Causal Effect Estimation; The causal model is fit to the input data, and then two systems, one intervened with a seasonal intervention x_s and one intervened with a zero intervention (0) are compared. The difference between the value of the two systems is the causal effect. C) Study Specific Adaption; Causal effects are estimated in 20-year moving windows across the 43-year time series, allowing the derivation of a causal-effect time series and its trend.~~

Figure 5. Schematic illustration of the causal inference framework applied in this study. A) Causal Discovery; PC and MCI algorithms examine statistical conditional independences of relationships between variables, which in turn are used to draw the causal graph. B) Causal Effect Estimation; The causal model is fit to the input data, and then two systems, one intervened with $do(X = \mu)$ and one intervened with $do(X = \mu - \sigma)$, representing typical and reduced trigger-variable conditions respectively, are compared. The difference between the value of the two systems is the causal effect. C) Study Specific Adaption; Causal effects are estimated in 20-year moving windows across the 43-year

2.5.1 Causal Discovery

For the causal discovery we use PCMCI+ ~~(Gerhardus and Runge, 2020; Runge et al., 2023), with~~ (Runge, 2020; Runge et al., 2023) , motivated by the multivariate structure of our system as discussed in Section 1.2. PCMCI+ extends the original PCMCI algorithm (Runge et al., 2019) by additionally enabling the detection of contemporaneous causal links, i.e. causal relationships occurring within the same time step, alongside lagged relationships (Runge, 2020). This extension is relevant for our setup, as some hydrological interactions may occur within a single biweekly time step. The analysis was conducted using the Tigramite Python package (https://github.com/jakobrunge/tigramite), which implements both PCMCI and PCMCI+. Our causal discovery is applied to eight biweekly variables obtained from time series data. These are river discharge, snowmelt, rain, glacier runoff, soil moisture, baseflow flux, evapotranspiration and temperature.

Additionally, we include the calendar week as an ~~index variable, which accounts~~ explicit index variable in the causal graph. This relaxes the stationarity assumption underlying PCMCI+ from stationarity across the full 43-year record to stationarity from year to year, thereby accounting for seasonal non-stationarity without requiring the variables to be detrended or deseasonalized prior to analysis. The calendar week variable is used only as a proxy for seasonality in the data, not as a variable with a direct causal effect. It captures the time of year, but should not be interpreted as a mechanistic driver of the hydrological variables studied here. ~~PCMCI+ is run with $\tau_{max} = 12$, thus comprising one contemporaneous and twelve biweekly lagged effects (six months).~~ Within PCMCI+ we specify a system of connections among the variables based on established hydrological and atmospheric relationships (DeWalle and Rango, 2008; Tague and Grant, 2009; Huss and Hock, 2018; Hammond and Kampf, 2020; Slater and Binley, 2021). These constraints are implemented as allowed relationships rather than fixed assumptions, restricting the search space without imposing causal links. Some link directions are predetermined by hydrological theory, while others remain unconstrained and are oriented by PCMCI+ using the PC algorithm's orientation rules. A schematic illustration of the assumed hydrological system is provided in Appendix A. The PCMCI+ algorithm consists of two substages. Firstly, the Peter Clark (PC) algorithm ~~which~~ builds a causal graph based on two key assumptions: the Markov condition (dependence implies connection) and the faithfulness condition (conditional independence implies no direct causation). Variables without unconditional dependencies are removed, after which the algorithm iteratively tests the remaining links for conditional independence, eliminating those that become independent once the common drivers and mediators are accounted for (see Fig. 5A, green arrow). This procedure continues until no further tests are possible, yielding the set of candidate parents (Runge et al., 2023, 2019). Secondly, the Momentary Conditional Independence (MCI) test evaluates the candidate parents using an expanded conditioning set (see Fig. 5A,blue arrow). By conditioning on the lagged parents of the driver and target variables, MCI refines the causal graph and reduces autocorrelation effects (Runge et al., 2023, 2019). The conditional independence test for ~~the~~ PCMCI+ can be adapted for the research problem at hand. We use the Conditional Mutual Information (CMIknn), as a conditional independence test, as it does not assume any parametric form for the ~~of~~ relationship between variables (Runge, 2018). This was crucial, given the presence of nonlinear relationships in our system.

2.5.2 Causal Effect Estimation

While the causal graph reveals the presence and direction of causal effects between variables over time, it does not quantify the strength of these effects. To estimate the magnitude of the causal relationships, causal effect estimation is conducted (see figure 5B). ~~After the full causal model is fit using the input data and parametric assumptions, an intervention can be introduced into the model using causal "do" calculus, or in this case optimal adjustment. By comparing two systems that are differently intervened, the difference in predictions provides the final causal effect (Runge et al., 2023; Runge, 2021). This is done using an estimator which can be selected for the examined study setup (Runge, 2021). For our setup we utilize a~~ We identify the causal effect via the adjustment formula $E[Y|do(X)] = \sum_Z E[Y|X,Z]\,P(Z)$ (Pearl, 2000; Runge, 2021), where Y is the target variable (river discharge), X is the trigger variable (snowmelt or rain), and Z denotes the adjustment set identified from the causal graph. The random forest (RF) estimator ~~to~~ is used solely as a non-parametric parametrization of the conditional expectation $E[Y|X,Z]$, not as a causal model itself (Breiman, 2001; Geurts et al., 2006). It is trained to predict river discharge given the trigger variable and the adjustment variables simultaneously. We use an RF estimator for this purpose to account for the versatile, non-linear nature of the relationships examined in this study, since the RF does not presume the type of relationship between two variables~~Breiman (2001); Geurts et al. (2006).~~ . Once fit, the causal effect is computed as the difference between model predictions under two different interventions on X (described below), evaluating the identified quantity $E[Y|do(X)]$ rather than reflecting model sensitivity. Because X influences Y both directly and indirectly, through mediating variables and across multiple time lags (see Fig. 5A), the resulting causal effect corresponds to the sum of path coefficients across all lags in the causal graph. It thus reflects the net effect of a unit change in the trigger variable on annual streamflow, integrated over the full lag structure. This combines both short-run and longer-run, potentially opposing, contributions into a single interpretable quantity. While Figure 5 provides a schematic overview of the overall framework, Figure 6 illustrates the underlying mechanics of the causal inference workings in more detail, walking through the causal graph, query, the resulting adjustment set, the random forest, and the resulting effect estimate for an example basin. We configure the RF with 1000 estimators to enhance model robustness, using the absolute error criterion to make the model more sensitive to small deviations in the data. To avoid overfitting, the maximum depth is set to 10, as this value results from a global hyperparameter search in which different tree depths were evaluated across all basins and time periods.

Since the resulting effect estimates are directly shaped by how the intervention is defined, the intervention in our causal effect estimation setup has to ~~reflect conditions that may realistically occur in the data. In our case with multiple basins that~~ remain within the support of the observed data, so that the resulting estimate is not driven by model extrapolation. Our basins vary in location, topography, and climate~~, another requirement for the intervention is the comparability~~ . This means the method must also be comparable across basins. Therefore, in our setup the intervention is not a single global value~~but it~~ , but is based on the seasonal structure of each basin and ~~to~~ the specific time lag under investigation. For ~~, each basin ,~~ each basin and year, we divide the variable time series into 26 parts, representing the seasonal cycle of the year. For ~~every~~ each of these 26 parts, we compute the mean (μ) and standard deviation (σ) of the trigger variable (snowmelt or rain) across all years ~~and apply it~~

~~as the intervention value for the corresponding period in specific position within the seasonal cycle.~~ within the corresponding window. We define two interventions per seasonal block: $do(X = \mu)$, representing typical conditions, and $do(X = \mu - \sigma)$, representing reduced snowmelt or rainfall conditions consistent with projected reductions in snowpack under climate change. Both interventions remain within the support of the observed data, avoiding the extrapolation issues associated with a zero intervention.

Since the resulting causal effect thus depends both on how strongly discharge responds to the trigger variable and on the magnitude of the anomaly used in the intervention, we additionally report σ itself as a measure of anomaly magnitude, and the ratio $\beta = CE/\sigma$ as an isolated measure of the coupling strength between the trigger variable and discharge, independent of anomaly magnitude. This decomposition allows us to distinguish whether a trend in the causal effect reflects a change in how strongly the trigger variable itself deviates from typical conditions, a change in how discharge responds to a given deviation, or both. We ensure that these block-specific interventions and the responses of the target are associated with the seasonal block they represent ~~, also intervening~~ by additionally fixing, rather than causally intervening on, the index variable (calendar week) to the corresponding value. This way the interventions and responses are anchored in time and correctly aligned with each seasonal block.

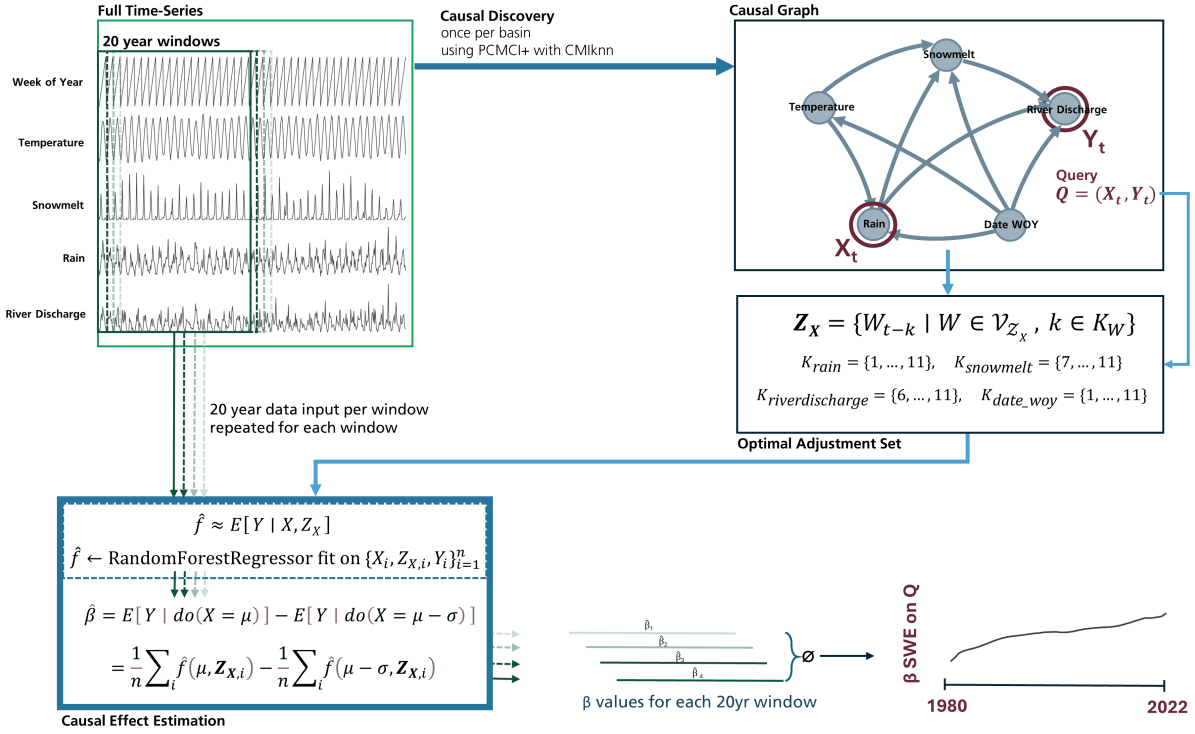


Figure 6. Illustration of the causal effect estimation procedure for an example basin: the causal graph identified during causal discovery with its lag structure, the resulting adjustment set Z for the trigger variable snowmelt, and the intervention design comparing $do(X = \mu)$ and $do(X = \mu - \sigma)$. The reported causal effect corresponds to the sum of path coefficients across all lags shown here.

We run the causal effect estimation for two variables. Firstly to estimate the causal effect of snowmelt on river discharge and secondly to estimate the causal effect of rain on river discharge. For both snowmelt and rain we use the same methodological setup. The causal effect estimation is run using a 20 year moving window, over our 43 years of data. For every period used, we determine the interventions separately using the corresponding time series. This 20-year window size balances the need for sufficient data points to reliably estimate causal effects ~~while enabling the detection of long-term temporal trends.~~ with limiting the degree of temporal autocorrelation introduced by overlapping windows; a 30-year window, for instance, would result in 29 of 30 years overlapping between adjacent windows. Multiple window sizes were evaluated during development, and 20 years was selected as an appropriate compromise between these two considerations. We then calculate the causal effect as the difference between the model prediction under the ~~blockwise~~ $do(X = \mu)$ intervention (5B, orange arrows) and the prediction under ~~an intervention in which all snowmelt related lagged values are set to zero~~ the $do(X = \mu - \sigma)$ intervention (5B, dark red arrows). This yields a total causal effect per 20 year period, which we then divide by the mean river discharge of the corresponding 20 year period. We average these effects by year, which results in a 43 year time series (5C). ~~Finally~~

Finally, we apply a ~~a~~ Theil-Sen estimator ~~and~~ together with the Hamed-Rao test, an extension of the Mann-Kendall test that accounts for autocorrelated data (Hamed and Ramachandra Rao, 1998), per basin and target variable. If in a basin at least one yearly average is zero, we exclude the basin from the trend analysis, as zeros near the edges of the time series can lead to unstable or notably steep trend slopes.

3 Results

3.1 Variable Trends

The normalized Theil-Sen trends of all variables in the analyzed basins~~were computed using the basin mean and the maximum absolute value for each variable, allowing for comparability across basins and variables. These trends~~, computed as described in Section 2.4, are illustrated in figure 7. A selection of basins, together with the corresponding causal trends, is examined in more detail in Section 3.4. As a comprehensive discussion of all variables and basins is beyond the scope of this publication, the full set of statistics per basin is provided in the supplementary materials (Appendix B).

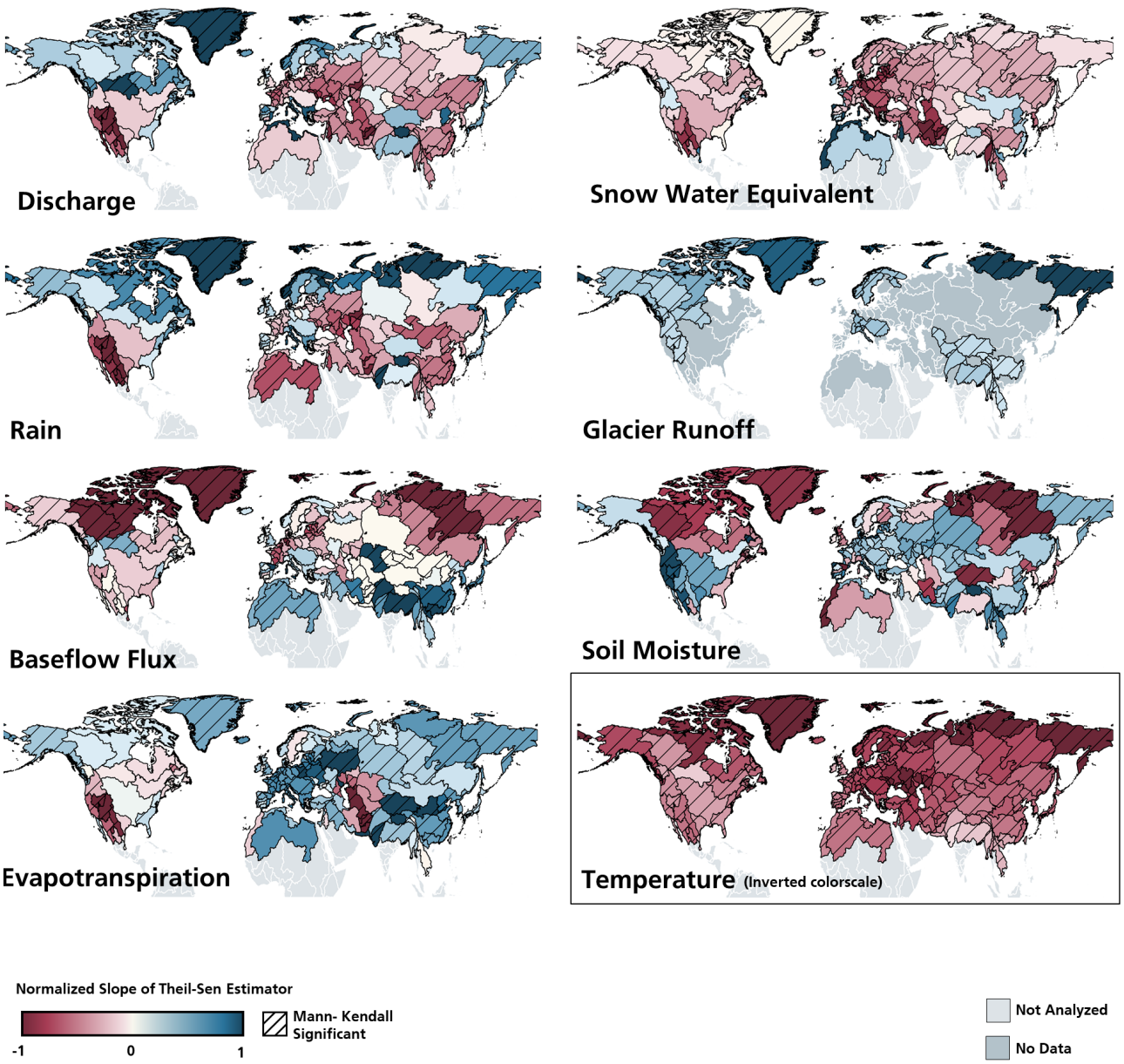


Figure 7. Normalized Theil-Sen trend with Mann-Kendall significance for the period 1980-2022 over all utilized variables in the 119 analyzed river basins. The color scale for all plots is scaled using the 5% and 95% percentile to ensure comparability between the different variables). The colorscale for the temperature is inverted.

Figure 8 contains the same information as figure 7~~, however~~. However, the basins are grouped by their river discharge, snow, and rain trend slopes, to generate a general impression of the dynamics in the basins. Note that for visualization purposes we refrained from generating intermediate categories~~, therefore also minor ,~~. Therefore, minor and non-significant trends were also

considered for the grouping. Even though eight groups are possible, there are four groups to which a majority of the analyzed basins can be attributed (105/119). ~~52~~ Fifty-two basins saw a decreasing trend for river discharge, SWE, and rain (purple). An additional twelve basins saw a decrease in river discharge and SWE but an increase in rain (green). This contrasts with 28 basins where the SWE decreased but rain and river discharge increased (orange). Finally the group where river discharge and rain were decreasing comprises 13 basins (blue). Considering these groups, the data furthermore suggests that in nearly all Arctic and Pan-Arctic basins, with the exception of the Yenisey Basin, the SWE was decreasing while rain was increasing, with various outcomes on the river discharge. Also, in the latitude band south of the Arctic, between around 60° and 20° North, a predominant majority of basins saw a decreasing trend in all three variables considered for the grouping.

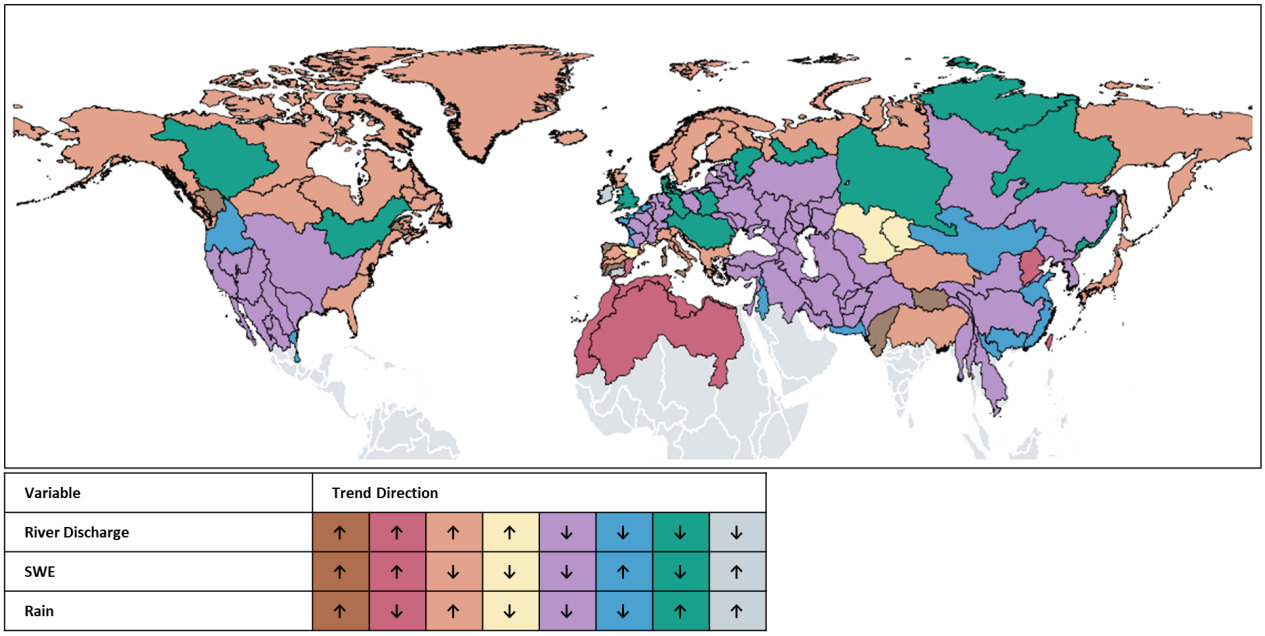


Figure 8. The 119 analyzed river basins, categorized by their river discharge, snow, and rain trend slopes and indicated by the different colors.

3.2 North Hemisphere Causal Trends

The causal effect trends for snowmelt and rain on river discharge were assessed across all 119 basins, as shown in figures 9 and 10 respectively. Areas colored in light brown were examined but no causal link, effect, or trend could be derived. This does not imply that no connection exists between the trigger variables (snow and rain) and the target variable (river discharge), or that no trend is present, but rather that our setup could not detect a connection, or the basin was excluded due to years with zero values. For the causal effect of snowmelt on river discharge, our method detected a continuous ~~effect and thus~~ trend in 73 basins~~, out of these32~~. Of these, 60 had a positive trend, ~~29 of those trends~~ 12 of which were significant. ~~Of the 41~~

basins with negative trends, 34 had a significant trend. For the causal effect of rain on river discharge, the method detected a continuous effect and therefore trend in 117 114 basins. The effect of rain on river discharge was positive in 57 67 basins (51 significant), and negative in 60 basins (56 47 basins (31 significant). The largest increase for the causal effect of snowmelt on river discharge was found in the Dnieper basin in eastern EuropeColumbia basin (USA and Canada). In contrast, the steepest decrease in the causal effect of snowmelt on river discharge occurred at the Mediterranean Sea east coast basin , which includes southern Türkyie, and parts of Lebanon, Syria, Israel, Jordan and Palestinein the Ziya He Interior basin in China. For rain the corresponding extreme values were found in the Hamun-e Mashkid basin in Iran Lena basin in Russia (steepest increase), and in the Rio Grande in the USA and Mexico Sweden basin (steepest decrease). If normalized with the basin mean, the steepest increase is to be found in the Central Iran (snowmelt) and on the Siberia West Coast (rain), thee steepest decrease in the Nelson basin (Canada, snowmelt), and on the North West coast of Mexico (rain). Overall, for all regions where a trend was calculated, As the majority of basins showed a positive causal trend for snowmelt, as was also the case for rain, no apparent overarching correlations or patterns emerged, neither for trend direction nor trend magnitude. Thus, no latitude or mountain effect could be observed when correlating the trend slope with the corresponding data. Furthermore, no correlation to the snow dominance (compare figure 2) or the overall discharge of the corresponding rivers could be identified. All results and trends can be found with the variable trends, grouped by basin, in Appendix B.

To better understand the drivers behind these causal effect trends, we examine two components separately: how strongly the trigger variable itself deviates in a poor snowmelt or rain year compared to a typical year (the anomaly magnitude), and how strongly river discharge responds to a given anomaly (the sensitivity, independent of how large that anomaly is, called coupling strength). For snowmelt, the anomaly magnitude increased in nearly all basins (72 of 73, 15 significant), whereas the coupling strength of discharge to snowmelt showed no consistent direction, increasing in 27 basins and decreasing in 42 (12 vs. 24 significant, respectively). For rain, the anomaly magnitude increased in every basin (118 of 118, 113 significant), while coupling strength again showed no consistent direction, increasing in 47 basins and decreasing in 62 (27 vs. 41 significant, respectively). This suggests that the predominantly positive causal effect trends for snowmelt, and the majority of positive trends for rain, are mainly driven by growing anomalies in snowmelt and rain themselves, rather than by river discharge becoming consistently more sensitive to them.

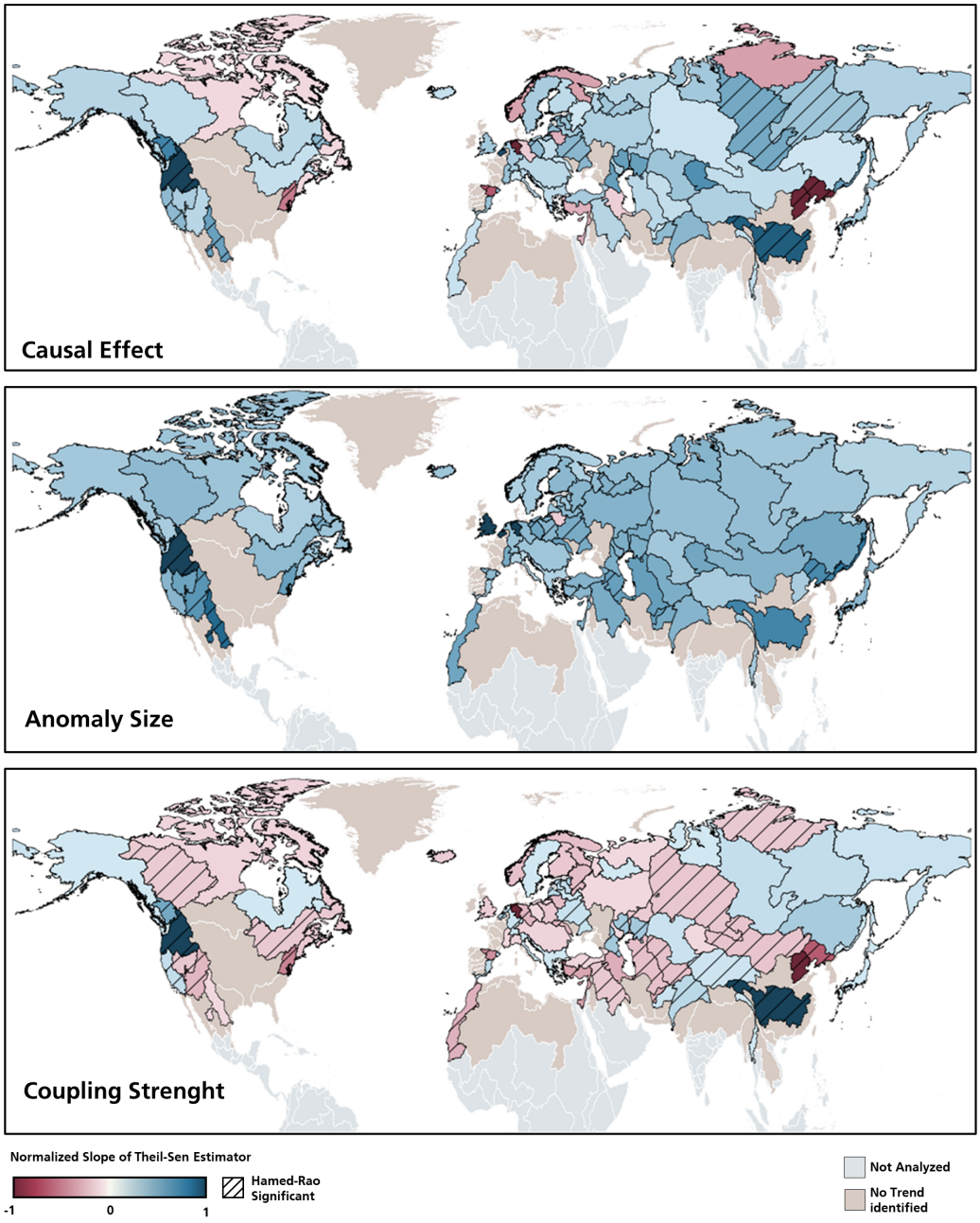


Figure 9. Normalized Theil-Sen ~~trend~~ trends with ~~Mann-Kendall~~ Hamed-Rao significance for the causal effect of snowmelt on river discharge between 1980 and ~~2022.~~ 2022, decomposed into three components (top to bottom). Causal Effect: $CE = E[Y|do(X = \mu)] - E[Y|do(X = \mu - \sigma)]$, normalized by mean river discharge, where Y is river discharge and X is snowmelt. Anomaly Magnitude: the trigger-variable anomaly σ used in the intervention, normalized by mean river discharge, reflecting how strongly snowmelt deviates in a poor snowmelt year relative to a typical year. Coupling Strength: $\beta = CE/\sigma$, the isolated response of discharge per unit of snowmelt anomaly, independent of anomaly size.

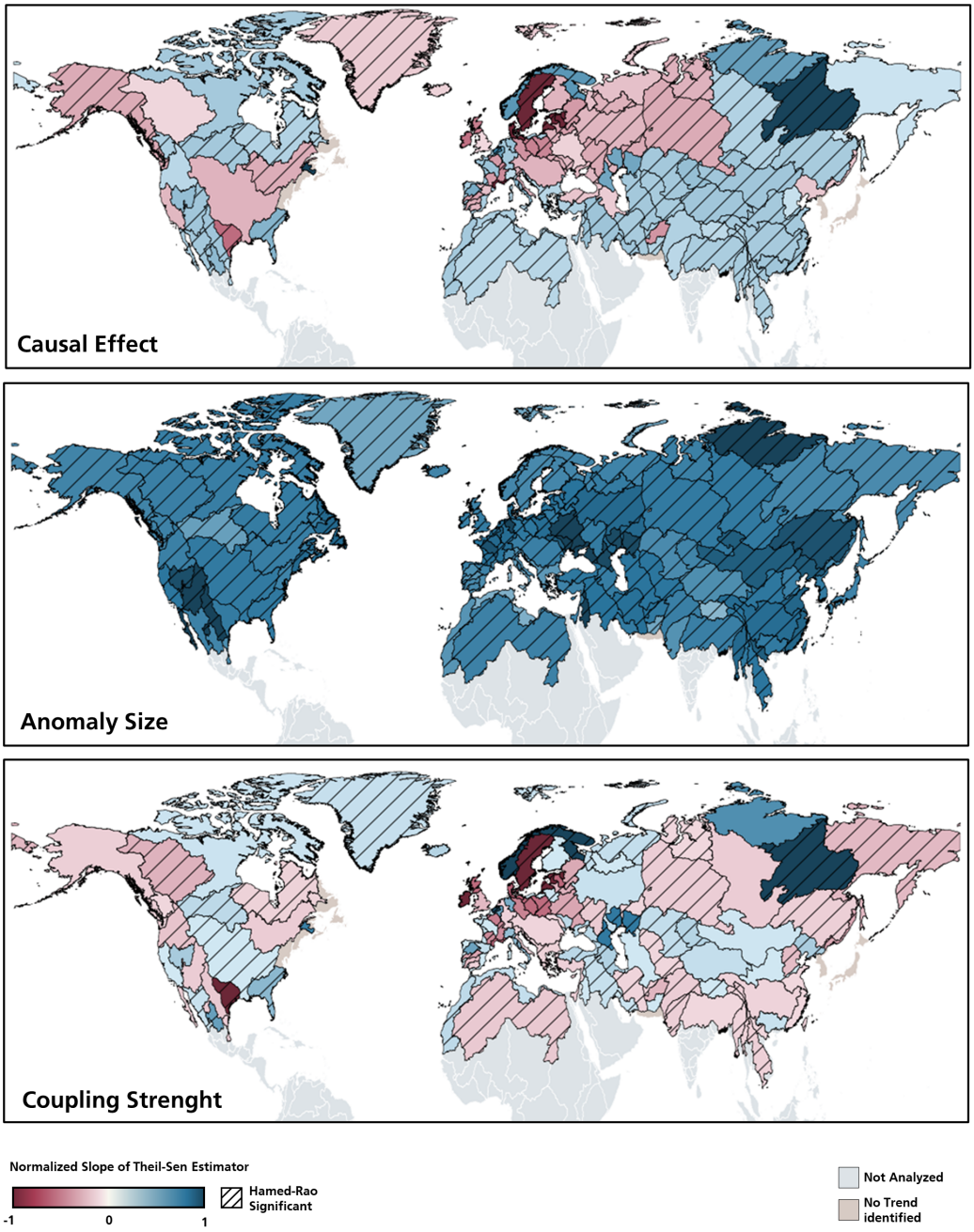


Figure 10. Normalized Theil-Sen ~~trend~~ trends with ~~Mann-Kendall~~ Hamed-Rao significance for the causal effect of rain on river discharge between 1980 and ~~2022.~~ 2022, decomposed into three components (top to bottom). Causal Effect: $CE = E[Y|do(X = \mu)] - E[Y|do(X = \mu - \sigma)]$, normalized by mean river discharge, where Y is river discharge and X is rain. Anomaly Size: the trigger-variable anomaly σ used in the intervention, normalized by mean river discharge, reflecting how strongly rain deviates in a poor rain year relative to a typical year. Coupling Strength: $\beta = CE/\sigma$, the isolated response of discharge per unit of rain anomaly, independent of anomaly size.

3.3 Using Causal Effects as Indicators of Water Stress

One reason to study the relationship between SWE and river discharge, or other measures of water availability, is the increasing occurrence of droughts and snow droughts due to climate change (Cowherd et al. (2023); Gottlieb and Mankin (2024)). Identifying regions where SWE is declining alongside river discharge, can therefore indicate where snow loss is a key driver of water stress, given the degree of snow dominance in those basins. Relying on the variable trends of SWE and river discharge, we used our results to identify such regions in our scope. A majority of the basins with a negative discharge trend also have a negative SWE trend (64/79). The remaining 15 basins that show a negative discharge trend despite an increasing SWE trend are shown in light green in figure 11. However, apart from the Fraser basin (USA/Canada), these all ~~lie in rain-dominated~~ are located in rain-dominated or very arid regions. In 45 of the 64 basins with decreasing discharge and decreasing SWE our method was able to identify a causal trend. Of those ~~22~~ 38 showed an increasing causal effect trend (blue in figure 11). In another ~~23~~ 7 basins the causal effect of snowmelt on river discharge was decreasing (red in figure 11). ~~Overall 20 out of the 22 basins with decreasing river discharge trend, decreasing SWE trend, and increasing causal effect trend of snowmelt or river discharge are located on the Eurasian landmass.~~

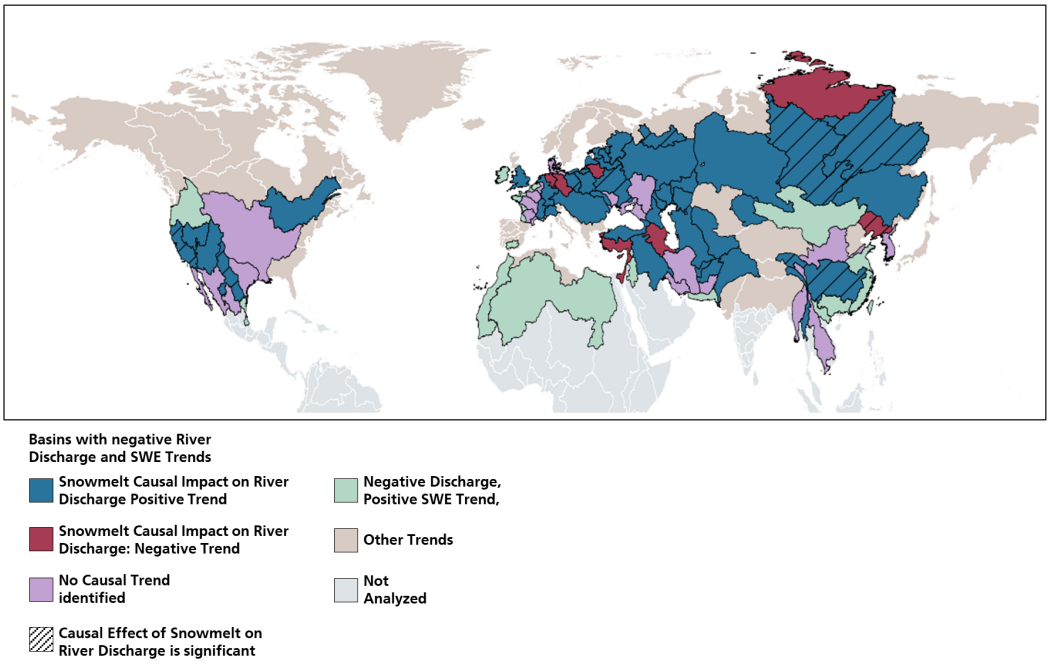


Figure 11. River basins with negative river discharge and rain trend, colored by the trend of the causal effect of snowmelt on river discharge.

3.4 Exemplary Basins Analysis

As an analysis of all examined basins would fall outside the scope of this publication, we selected six basins on three continents for an exemplary analysis in this section. The basins can all be attributed to the three main groups setup in section 3.1. Figure

12 ~~,~~shows an overview of the course of the causal effects of snowmelt and river rain on river discharge, from 1980-2022 for the exemplary basins. We selected the basins based on location, their classification in section 3.1, and the dynamics among the variables. Note ~~,~~ that some basins span over multiple climate zones and encompass several land-cover types, as well as subbasin dynamics~~, therefore the analysis on~~ . Therefore, the analysis of the basin might fall short of explaining the complete range of mechanisms and developments that took place within the basin region during the study period.

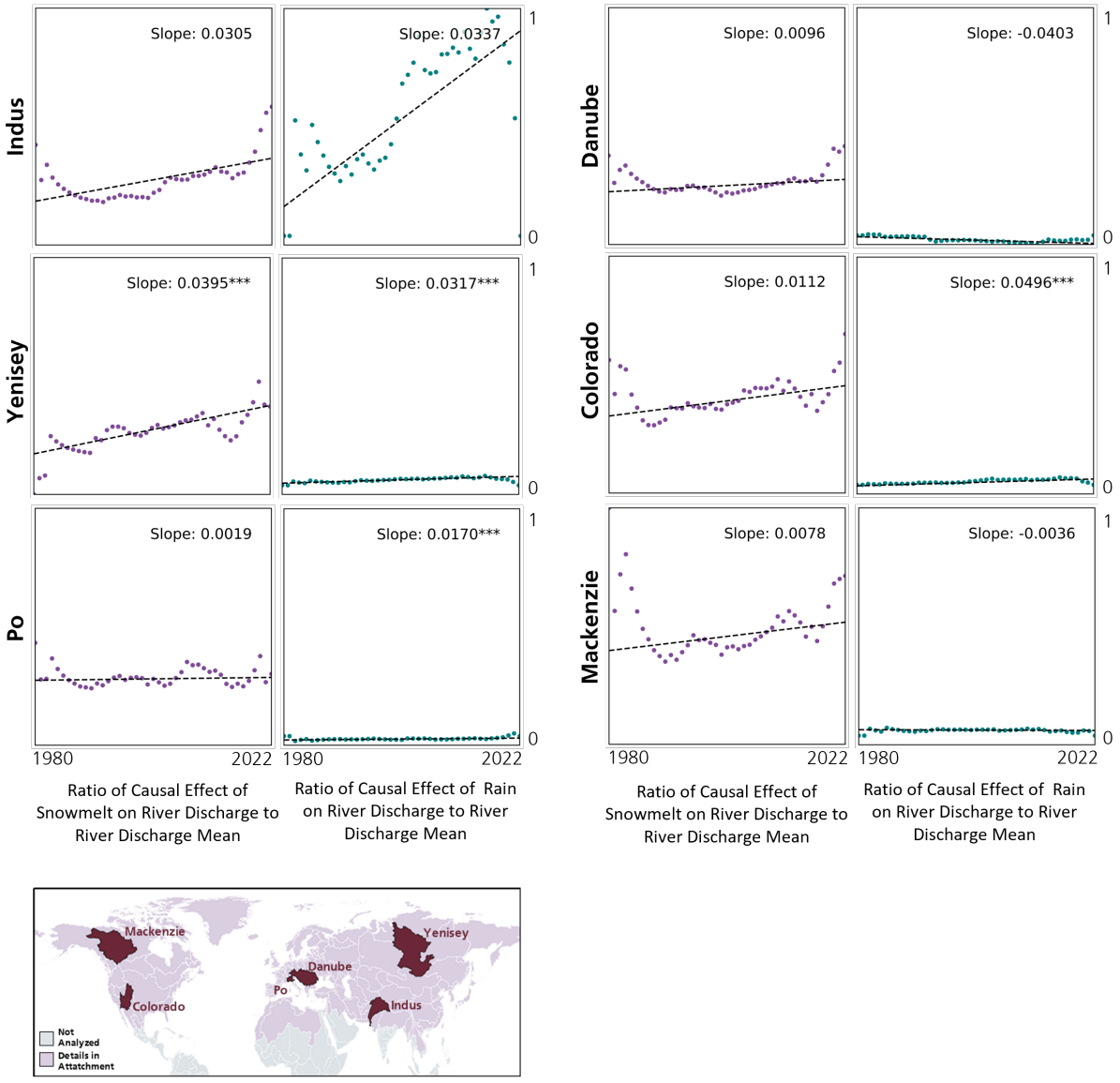


Figure 12. The causal effect of snowmelt on river discharge (both columns on the left - purple) over the examined time period and the six exemplary basins. Causal effect of rain on river discharge (both columns on the right - teal) over the examined time period and the six exemplary basins. Displayed as a ratio of causal effect to mean discharge. Significant (Hamed-Rao test) trends, assessed at the 95% confidence level ($p<0.05$) are indicated with asterisks (***). The dots mark the average values per year, the dashed black line marks the Theil-Sen slope per basin. The exemplary basins are marked on the map.

3.4.1 Mackenzie

The Mackenzie basin is located in northern Canada and mainly characterized by a subarctic climate (Beck et al., 2023). The basin extends approximately from 52°N to 69°N, contains two major lakes (Great Bear Lake, Great Slave Lake) and is primarily dominated by tundra and taiga land cover types (Friedl et al., 2019). Generally the discharge in the Mackenzie basin is mainly snow dominated ~~Woo et al. (2018)~~(Woo et al., 2018), and while glacier runoff plays a role as well it appears to be less dominant as in other, more coastal basins adjacent to the Rocky Mountains (Clarke et al., 2015). In our categorization (Figure 8), the basin shows a decreasing SWE trend alongside an increasing rain trend, resulting in an increasing discharge trend. However, these trends are relatively stable. In contrast, glacier runoff has increased significantly over the study period, indicating that glaciers are melting and their storage capacity is diminishing. Additionally, both baseflow flux and soil moisture trends are significantly negative. ~~When examining the causal effect trends, they appear somewhat counterintuitive, as both the effects of rain and snow~~ The causal effect of snowmelt on river discharge ~~are negative. For snow, this corresponds to the variable trend itself , whereas for rain, it acts in the opposite direction. This pattern might be explained by a combination of two processes: a gradual shift from a snowmelt-driven regime towards an increasingly rainfall-driven regime, and a higher infiltration potential resulting from increased permafrost thaw due to climate change~~showed a positive trend in the Mackenzie basin. This coincided with a growing snowmelt anomaly, while the responsiveness of river discharge to snowmelt itself decreased significantly, suggesting that the growing anomaly, rather than a stronger coupling between snowmelt and discharge, drives this trend. For rain, the causal effect on river discharge showed a negative trend, even though the rainfall anomaly grew significantly as well. Here the responsiveness of discharge to rain decreased significantly, which appears to outweigh the growing rainfall anomaly and drive the observed decrease.

3.4.2 Colorado

The Colorado stretches from 32°N to 43°N over the southwestern United States and northern Mexico. Despite the mountains in the northeast, the basin generally has an arid climate (Beck et al., 2023), and is mainly covered by grass-, and shrublands (Friedl et al., 2019), as well as extensive agriculture areas (Norton et al., 2021). In the Colorado basin, both snow and rain have declined, corresponding with the observed decrease in river discharge. ~~Also both the snowmelt~~For snowmelt, the causal effect on river discharge ~~and the rain~~ showed a positive, non-significant trend, coinciding with a significant increase in the snowmelt anomaly, while the responsiveness of discharge to snowmelt decreased significantly, suggesting that a weakening coupling between snowmelt and discharge counteracts, but does not outweigh, the growing anomaly. For rain, the causal effect on river discharge ~~have decreased. Thus overall, the basin is experiencing lower flow conditions due to reductions in both SWE and precipitation. The causal effect trends suggest that rainfall dynamics remain largely unchanged, apart from a general decrease in volume. In contrast, shorter and faster snowmelt periods appear to reduce snowmelt's ability to sustain river flow year-round, either directly or via intermediate drivers such as baseflow flux or soil moisture. Consequently, snow not only diminishes in quantity but also loses its effectiveness in maintaining streamflow.~~ showed a significant positive trend, coinciding

with a significant increase in the rainfall anomaly, while the responsiveness of discharge to rain decreased, indicating that the growing rainfall anomaly, rather than a stronger coupling, drives this trend.

3.4.3 Danube

The Danube is the largest river basin in central Europe, following an eastward course reaching from the Alps (8°E) to the Black Sea (45°E) and laying in between 42°N and 52°N. The climate is mainly humid ~~, continental~~ in the North of the basin and subtropical in the south, with some arid steppes in the east (Beck et al., 2023). The basin is located over a series of highly populated and industrialized regions, and generally covered with either forest, or grass- and croplands (Friedl et al., 2019). In the Danube SWE ~~is~~ was decreasing, rain ~~is~~ was increasing, and discharge ~~is~~ was decreasing slightly. ~~The causal effect trends are similar to those of the Mackenzie and Colorado, with both~~ For snowmelt, the causal effect ~~of snowmelt and the rain causal effect~~ on river discharge ~~decreasing. In the Danube however, the precipitation contribution is generally less snow dominated than in the Mackenzie (compare figure 2), and the trends for both baseflow flux and soil moisture are increasing. The results suggest that river discharge in the Danube Basin is becoming less directly controlled by individual precipitation components. Instead, buffering processes in the soil, vegetation, and baseflow flux may be strengthening, which appears to dampen the immediate hydrological response. At the same time, higher evaporation rates and anthropogenic interventions might cause a larger share of precipitation to no longer contribute directly to river discharge. Overall, this points to a more diffusely regulated flow regime in which the direct contributions of rain and snow seem to be declining, even though~~ showed a positive trend, coinciding with an increasing snowmelt anomaly, while the responsiveness of discharge to snowmelt decreased, though neither of these trends was significant. For rain, the causal effect on river discharge showed a negative trend, coinciding with a significant increase in the rainfall anomaly, alongside a decrease in the ~~climatic conditions themselves are changing.~~

responsiveness of discharge to rain, though neither of these last two trends was significant, suggesting that the growing rainfall anomaly outweighs any change in coupling in driving the negative trend.

3.4.4 Po

The Po basin is one of the smallest basins in the analysis, located south of the Alps in mainly northern Italy and to a small part in southern Switzerland between 44°N and 46°N. It is characterized by ~~continental~~ alpine climate in the north and a humid climate in the rest of the basin (Beck et al., 2023). The basin is predominantly characterized by croplands, with occasional forests and major cities such as Milan or Torino (Friedl et al., 2019). The trends for river discharge, and SWE are decreasing, while the rain trend is increasing. The trends, for soil moisture and baseflow flux are contrary to each other, but in a comparatively flat nature. ~~As in all exemplary basins, the glacier runoff is increasing, which in a small basin as the Po might have a larger influence compared to the larger basins that are also showed in this section. While most large-scale trends remain relatively flat, the causal relationships between precipitation and discharge reveal a more dynamic picture. Both snowmeltand rain causal effects increase, but snowmelt rises significantly faster. Despite declining SWE, streamflow becomes progressively snow-controlled. As the snowpack diminishes, snowmelt concentrates in spring, with remaining snow reliably driving discharge. Rainfall's more modest increase reflects greater variability. The basin thus becomes dependent on fewer but structurally critical melt events.~~

This intensification of snow dependence despite ongoing snowpack loss renders the Po basin particularly vulnerable to further SWE reductionsFor snowmelt, the causal effect on river discharge showed a slight positive trend, coinciding with a slight increase in the snowmelt anomaly and a slight decrease in the responsiveness of discharge to snowmelt, though none of these trends were significant. For rain, the causal effect on river discharge showed a significant positive trend, coinciding with a significant increase in the rainfall anomaly and a significant increase in the responsiveness of discharge to rain, indicating that both the growing anomaly and a strengthening coupling between rain and discharge contribute to this trend.

3.4.5 Yenisey

Reaching, from arid steppes in Mongolia (46°N) over subarctic climate with tundra and taiga to the estuary into the Kara Sea in Siberia/Russia (71°N), the Yenisey basin is fairly diverse and the largest one in this exemplary analysis. In the Yenisey basin river discharge, SWE, and rain all experienced negative trends from 1980 to 2022, whereby the trends for river discharge and SWE are steeper and significant, while the rain trend is only subtly negative and not significant. Both, the causal effect of snowmelt and rain on river discharge were increasing slightly over the study period. As the Yenisey is generally a snow-dominated basin (compare Figure 2), and the trends for soil moisture and baseflow flux are both significantly decreasing, the observed causal dynamics appear to be well represented. Despite the decreasing SWE trend, snow remains the most important contributor to river discharge . With rainfall remaining relatively stable, and both soil moisture and baseflow flux showing negative trends, the increasing causal effects of rain and snow For snowmelt, the causal effect on river discharge showed a significant positive trend, coinciding with a positive trend in the snowmelt anomaly and a positive trend in the responsiveness of discharge to snowmelt, indicating that both the growing anomaly and an increasing coupling between snowmelt and discharge contribute to this trend. For rain, the causal effect on river discharge likely reflect changes in the basin's storage behavior. As these storage components decline, precipitation and snowmelt events translate more directly into runoff. In the Yenisey, this suggests that the role of snow as an active storage and release component is becoming increasingly important, as indicated by the rising causal influence of snowmelt on dischargeshowed a significant positive trend, coinciding with a significant increase in the rainfall anomaly, while the responsiveness of discharge to rain showed a non-significant negative trend, suggesting that the growing anomaly, rather than a stronger coupling, drives this trend.

3.4.6 Indus

Among others, the Indus Basin is home to some of the tallest mountains in the world (e.g. K2) as well as and Nanga Parbat) and is highly glacierized with some of the world's largest non-polar glaciers (e.g. Siachen Glacier). The basin which is located between 23°N/66°E and 38°N/83°E, is climatically very diverse, reaching from subarctic and tundra mountain climate in the north, subtropic and savannah climate in the central basin and hot arid desert climate in the south (Beck et al., 2023). The land cover is similarly diverse with the mountains in the north, a mix of grass- shrub- and croplands in the center and along the Indus river itself, and barren deserts in the southeast (Friedl et al., 2019). The Indus basin has seen a significant decrease of SWE, discharge, and a non-significant decrease of rain. All these trends are, if not all significant, of a medium steepness in the global comparison. The causal effect of snowmelton river discharge has increased over our study period,

while For snowmelt, the causal effect of rain on river discharge has remained essentially showed a positive, non-significant . Since the Indus basin is highly glacierized, glaciers play a major role in streamflow generation. In contrast, summer rainfall often coincides with peak glacier melt, when meltwater already dominates streamflow. This temporal overlap might explain why the causal effect of rain remains essentially non-significant, as rainfall contributions are masked by the glacier melt signal during the main runoff season (Lutz et al., 2014; Bolch et al., 2012; Pritchard, 2019; Immerzeel et al., 2010). Thus, the increasing causal effect of snowmelt trend, coinciding with a non-significant increase in the snowmelt anomaly, while the responsiveness of discharge to snowmelt showed a significant positive trend, suggesting that an increasing coupling between snowmelt and discharge contributes to this trend more than the anomaly itself. For rain, the causal effect on river discharge corresponds to increased winter precipitation, which typically occurs before the main glacier melt season. During this period, the snow cover also protects the glacier surface from direct exposure (Lutz et al., 2014; Pritchard, 2019), delaying melt onset and stabilizing runoff. In contrast, summer rainfall often coincides with peak glacier melt, when meltwater already dominates streamflow, which potentially explains the decreasing causal effect of rain on river dischargein the Indus basinshowed a positive, non-significant trend, coinciding with a significant increase in the rainfall anomaly, while the responsiveness of discharge to rain showed a significant negative trend, suggesting that the growing anomaly, rather than a stronger coupling, drives this trend, despite the weakening coupling between rain and discharge.

3.5 Consistency and Fluctuations of Trends

For this study, only peer-reviewed and validated data were utilized. However, the methodological outcomes cannot be adequately validated with independent data, as no comparable datasets documenting the contribution of individual factors to river discharge exist with the required spatial and temporal scope. The analysis of the calculated data shows that

This section assesses the internal consistency of the causal effect estimates: specifically, whether the estimated causal effects are stable within individual basins over time, or whether they are dominated by noise rather than reflecting a genuine underlying signal. This is distinct from a validation of the absolute values of the causal effects themselves, for which no independent data exist against which such a comparison could be made. Internal consistency is nonetheless a meaningful evaluation, since the absolute values of the causal effects depend on a wide variety of factors . These that are not always to be understood from the data or from the attributable to the real-world system alone, but also how capable the random forest is of recognizing to the capacity of the random forest estimator to resolve the effects of the individual variableson each other. Therefore, the most suitable approach to evaluate the performance of the method is to individual variables. We therefore focus on the dispersion of the results within the individual basins . individual basins as an indicator of estimation stability. A low coefficient of variation after trend correction indicates that the residual variability around the estimated trend is small relative to the mean, which we interpret as evidence that the method produces consistent rather than erratic results. For each basin, we calculate the coefficient of variation (CV) as well as a trend corrected version of it (Trend-CV) using the Theil-Sen slopes described in 3.2. The CV is defined as:

$$\text{CV} = \frac{\sigma}{\mu} \tag{1}$$

where σ is the standard deviation and μ is the mean of the dataset.

The Trend-CV respectively is calculated as follows:

$$\text{Trend-CV} = \frac{\sigma_{\text{residual}}}{\mu_{\text{residual}}} \tag{2}$$

Here, σ_{residual} is the standard deviation of the residuals, and μ_{residual} is the mean of the residuals, defined as:

$$\text{residual} = y_i - \hat{y}_i \tag{3}$$

where y_i is the actual value and $\hat{y}_i$ is the predicted value. CV and Trend-CV were calculated for the full time series of snowmelt and rain causal effects on river discharge, as well as for a truncated time series (1985–2017). This truncation is necessary because the moving window approach used in the method leads to smaller sample sizes at the beginning and end of the time series, compared to the center. A Wilcoxon signed-rank test reveals that a significant portion of the dispersion arises from these time series ends. Furthermore, comparing the CV with the Trend-CV indicates that the trend itself accounts for a substantial part of the observed dispersion. This pattern also holds for the Trend-CV, where the ends of the time series contribute markedly to the overall variability. A summary of the dispersion metrics is shown in figure 13.

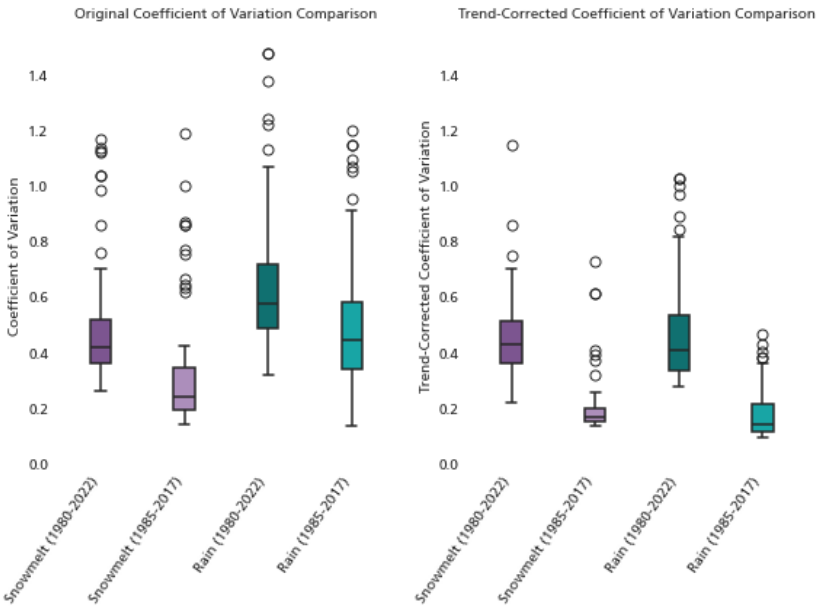


Figure 13. Measures of Dispersion for causal effect on river discharge trends of both snowmelt and rain over all basins. Left: coefficient of variation. Right: Normalized RMSE, corrected for the Theil-Sen trend displayed in section 3.2.

4 Discussion

4.1 Contextualization of Results

4.1.1 Global and Large-Scale Studies

As mentioned in the sections 2 and 3.5, no adequate and independent validation data ~~is~~ are currently available to validate ~~a study of the scope presented~~ the causal effect trends in this paper. While our ~~plausibility~~ sanity tests with modified trigger variables demonstrated that the method adequately captures such changes, this only validates its internal functionality and does not confirm the accuracy of the actual effects. Therefore, the study should be viewed as an experimental data analysis to test the applicability of the presented methods. Nevertheless, we aimed to contextualize our results with already published studies. Accordingly, we incorporated global studies from a review (Schilling et al., 2024) and conducted a systematic literature search via Web of Science (WOS), using various terms concerning SWE, streamflow and driving factors, subsequently evaluating their relevance to our findings. Given the use of partly identical data, the global trends align with those already published at the global level, as expected. While differences in aggregation and representation might result in differing interpretations, the trends presented here are consistent with what is to be expected and fall within the anticipated range (TWS; ~~Zhang et al. (2019)~~ Zhang et al. 2019, river discharge: ~~Shi et al. (2019); Park et al. (2024)~~Shi et al. 2019; Park et al. 2024, SWE; ~~Pulliainen et al. (2020)~~ Pulliainen et al. 2020, precipitation; ~~Sun et al. (2021)~~Sun et al. 2021, SM; ~~Mohseni et al. (2023)~~Mohseni et al. 2023, groundwater (baseflow flux); ~~Hasan et al. (2023), temperature~~Hasan et al. 2023, temperature: Wang et al. (2022), evapotranspiration ~~; Li et al. (2023)~~ Li et al. 2023).

~~Expanding the scope to river discharge contribution ,~~ When the scope is expanded to river-discharge contribution as well as ~~flood generating~~ flood-generating studies, several studies align with the general mechanisms and snow dominance depicted in our analysis (Do et al., 2020; Zhang et al., 2023; Robinson and Clark, 2020) on a global level, or on continental (Europe; ~~Jiang et al. (2022); Fang et al. (2024)~~Jiang et al. 2022; Fang et al. 2024, North America; ~~Li et al. (2019)~~Li et al. 2019) and Arctic scale ~~(Park et al., 2024)~~Park et al. 2024). These studies confirm the trends described in section 1.1, towards earlier and faster snowmelt periods. Examining the exemplary basins shows that the Colorado and Indus basins are well represented in the literature, the Danube, Po, and Mackenzie basins have somewhat lower coverage, and the Yenisey basin shows very limited documentation based on English-language publications. In terms of content, the smaller-scale studies confirm the global trends, and certain regional patterns emerge.

4.1.2 Basin-specific patterns

In the Danube and Po basins, which both have their headwaters in the Alps, the discharge in the entire basin is dependent on the corresponding snowpack, especially in drought years (Chen et al., 2020; Stagl and Hattermann, 2015; Guastini et al., 2019; Coppola et al., 2014; Vezzoli et al., 2015; Avanzi et al., 2024). ~~The causal trends in the Po and the Danube~~ For rain, the two basins developed in opposite directions~~for both rain and snowmelt. In the Danube both trends are negative~~: the causal effect

of rain on river discharge increased significantly in the Po, alongside a significant increase in both the rainfall anomaly and the coupling strength of discharge to rain, whereas in the ~~Po both are positive, suggesting that the hydrological mediation of precipitation is changing in different ways in the two basins~~Danube it decreased, despite a significant increase in the rainfall anomaly there as well, while the coupling strength of discharge to rain showed a non-significant decrease. For snowmelt, both basins showed a non-significant positive trend in the causal effect, alongside a non-significant increase in the snowmelt anomaly and a non-significant decrease in the coupling strength of discharge to snowmelt in both cases. In the Po, ~~increasing causal effects of both snowmelt and rain~~ the combined growth of the rainfall anomaly and an increased coupling between rain and discharge indicate that a larger fraction of precipitation is transformed into discharge directly, ~~with snowmelt gaining relative importance compared to rain~~ in a strongly ~~snow-dominated~~ snow-dominated and comparatively small basin. ~~Fewer but more concentrated melt and rainfall events increasingly control annual flow, and appear to make the system more sensitive to changes in SWE and event timing.~~ This is consistent with the higher contribution of snowmelt to total discharge in the Po compared to the Danube, where rainfall accounts for a larger share of the annual water balance (Stagl and Hattermann, 2015; Vyshnevskyi and Shevchuk, 2022; Formetta et al., 2022). In the Danube, by contrast, ~~decreasing causal effects for both components point to~~ the growing rainfall anomaly is not matched by a strengthening coupling, and instead the causal effect of rain on discharge weakens. This would be consistent with a more buffered flow regime, in which soil moisture, groundwater and human regulation increasingly decouple precipitation inputs from immediate river discharge~~. As a result, even with increasing rainfall the direct causal effects weaken, and low-flow resilience depends more on the state of subsurface and managed water stores than on single snowmelt episodes~~, though as neither the coupling strength trend nor the snowmelt trends in either basin reach statistical significance beyond the rainfall anomaly itself, we refrain from a stronger mechanistic interpretation of these patterns. Additional factors such as topography, river regulation and ~~urbanisation~~ urbanization may further shape ~~these contrasting~~ basin-specific responses but cannot be ~~fully~~ resolved without more detailed local analyses. In both basins, glaciers currently help to ~~stabilise~~ stabilize discharge as long as they continue to melt at approximately present rates (Van Tiel et al., 2021; Lambrecht and Mayer, 2024; Penna et al., 2017; Huss, 2011), which is consistent with global evidence for a ~~transient stabilising~~ stabilizing role of glacier melt under warming conditions (Ultee et al., 2022).

The Colorado basin shows similar characteristics with the Po and Danube basins, with headwaters in mountains flowing into a plain with limited snowfall. However, the plains in the Colorado basin are more arid than in the European examples, which imparts its specific characteristics to the basin. Therefore, the basin is very dependent on its seasonal ~~snow pack~~ snowpack (Webb et al., 2024), but as it is drier than the Po and Danube, the amount of summer precipitation seems to have a more crucial impact on the overall hydrological balance (Flynn et al., 2024; Ban et al., 2023). This is also supported by Wolf et al. (2023), who states ~~,~~ that groundwater is a crucial streamflow driver during late summer and autumn. Additionally the soil moisture seems to play a~~n~~not fully understood role in the Colorado basin, for example, Talsma et al. (2022) have observed strongly erratic behavior of soil moisture data in the Colorado Basin (as also seen in our findings), and Julander and Clayton (2018) found for small basins in Utah that above-average rainfall does not drive runoff proportionally. Also it is to consider that other storage mechanisms such as soil moisture and groundwater become more crucial, which complies

with the findings of Wolf et al. (2023) as well as Julander and Clayton (2018), even though they are declining (see figure 7). Overall this paints a picture of a basin that experiences increasingly dry conditions, and has to rely more and more on single weather events to recharge its storage, as the general storage level has decreased in the last years. The ~~causal effects of both snowmelt and rain on river discharge are both decreasing significantly. This indicates~~ coupling strength of discharge to snowmelt decreased significantly, and the coupling strength of discharge to rain decreased as well, despite significant increases in both the snowmelt and rainfall anomalies, indicating that rain and snowmelt are translated into runoff less efficiently than before. This decline in hydrological effectiveness has been demonstrated in recent years~~: even~~ . Even record-high snowpack in 2023 failed to adequately recharge groundwater reserves or generate proportional streamflow increases (Carroll et al., 2024). Recent isotope studies show that during peak snowmelt, streamflow is increasingly dominated by aged groundwater rather than direct snowmelt contributions, indicating that precipitation is increasingly delayed and decoupled from immediate runoff (Brooks et al., 2025). Taken together, earlier and faster snowmelt driven by warming temperatures compresses the melt period and reduces water availability during critical late-summer low-flow periods. Similarly, summer rainfall becomes increasingly decoupled from runoff generation, potentially due to increased evapotranspiration or limited soil infiltration capacity under water stress. Despite this declining efficiency, the causal effect of rain on river discharge showed a significant positive trend, and the causal effect of snowmelt a non-significant positive trend, driven primarily by the growing magnitude of the underlying anomalies rather than by a strengthening coupling between the trigger variables and discharge. The Colorado thus faces a dual challenge: declining water availability combined with ~~reduced efficiency of~~ a reduced efficiency in translating the water that does arrive ~~, a~~ into streamflow, even as increasingly extreme deficit years leave a growing mark on the causal footprint of both snowmelt and rain, a pattern that underscores the basin's heightened vulnerability to further climate change.

In the Arctic, the Mackenzie, but not the Yenisey, aligns with the general Arctic trend of increased discharge (Park et al., 2024), however in the Mackenzie the discharge trend is basically flat, while it is significantly decreasing in the Yenisey. Generally and comparable to the ~~alpine~~ Alpine basins, these basins see faster and shorter melt periods (Yang et al., 2021; Mavromatis et al., 2016). Also several regional dynamics seem to apply, for instance Krogh and Pomeroy (2018) showed that a series of snow-hydrological processes in a small subbasin of the Mackenzie are slowing down, and sublimation and evapotranspiration have dropped, mitigating the reduced precipitation in the subbasin. The latter is not true for the entire basin, ~~could however be an indication of~~ but could indicate changing dynamics within the basin, in which, ~~among deceasing~~ alongside decreasing soil moisture and baseflow flux trends, snow as a storage ~~becomes more important, as indicated by our findings.~~ component leaves a growing mark on river discharge, consistent with the positive causal effect trend we find for snowmelt in the Mackenzie. However, the underlying coupling strength of discharge to snowmelt decreased significantly in the Mackenzie, in contrast to the Yenisey, where the causal effect of snowmelt on discharge increased significantly, alongside a non-significant increase in both the snowmelt anomaly and the coupling strength of discharge to snowmelt. For the Yenisey, Zakharova et al. (2011) shows that over time, less snowmelt was ending up as river discharge in the region due to increased evaporation and sublimation. Also Gordeev et al. (2024) suggests that a decreasing influence of bogs could cause an observed increasing role of Al-rich colloids and subcolloids. These results suggest that rising temperatures increase sublimation, and

the correspondingly thawing permafrost allows for greater water infiltration into the ground (Kurylyk and Walvoord, 2021). ~~Consequently, less water flows directly into rivers. However,~~ , which would be expected to weaken, rather than strengthen, the direct coupling between snowmelt and discharge. Our finding of a slightly increasing coupling strength in the Yenisey does not straightforwardly align with this mechanism. It may instead reflect that reduced precipitation (both snow and rain) leads to lower soil moisture and groundwater recharge, making the storage function of SWE increasingly important as a more direct source of streamflow once other pathways are depleted. Therefore, although local research indicates increased infiltration of precipitation into the ground and delayed river flow, our ~~identified causal effects~~ results suggest that the ~~general pattern of decreasing total precipitation and increasing intra-annual variability supersedes changes in soil infiltration in terms of~~ growing magnitude of the snowmelt anomaly, and possibly this compensating storage effect, together outweigh any weakening of the snowmelt-discharge coupling in terms of the resulting causal effect on streamflow generation. ~~Therefore, an increasing causal influence of snowmelt on river discharge and changes in infiltration processes can occur simultaneously, reflecting that several hydrological developments can occur in parallel, although some may dominate at larger scales.~~ These dynamics could also apply for the Mackenzie basin, where permafrost is also thawing (Kurylyk and Walvoord, 2021), and apart from the river discharge and rain trend all other variable trends develop in the same direction as the trends in the Yenisey. Unlike the Yenisey, however, the coupling strength of discharge to snowmelt in the Mackenzie decreased significantly rather than increasing, suggesting that the two basins, despite comparable permafrost dynamics, differ in how effectively snowmelt anomalies are converted into discharge.

Since climate in the Indus basin is mostly dominated by the Westerlies instead of Monsoon seasons, as it is in other Himalayan basins, the Indus basin shares various similarities with other basins in this analysis. It has snow-rich, strongly glacierized mountains in the headwaters, and arid regions downstream. However, the Indus stands apart from Colorado, Danube, and Po, since its glacier mass surpasses the others by magnitudes. Therefore the main driver in streamflow generation is the glacier melt Immerzeel et al. (2010); Bolch et al. (2012); Yao et al. (2022) and snowmelt seems to only play a secondary role (Kumar et al., 2024; Soheb et al., 2024; Joshi et al., 2023; Shafeeque et al., 2023). Glacier melt has been increasing during our study period, though it is believed that peak water has not yet been reached ~~Lutz et al. (2014); Pritchard (2019). The increasing contribution of glacier melt, may explain why the~~ (Lutz et al., 2014; Pritchard, 2019; Huss and Hock, 2018). The coupling strength of discharge to snowmelt increased significantly in the Indus basin, while the coupling strength of discharge to rain decreased significantly. Both the causal effect of snowmelt and of rain on river discharge ~~remains essentially flat and~~ showed a positive, non-significant ~~, as their main occurrence mostly coincide.~~ trend, coinciding with a non-significant increase in the snowmelt anomaly and a significant increase in the rainfall anomaly. Since the Indus basin is highly glacierized, glaciers play a major role in streamflow generation, and summer rainfall often coincides with peak glacier melt, when meltwater already dominates streamflow. This temporal overlap might explain the decreasing coupling strength of discharge to rain, as rainfall's marginal contribution is increasingly masked by the glacier melt signal during the main runoff season (Lutz et al., 2014; Bolch et al., 2012; [illegible]. The increasing coupling strength of discharge to snowmelt, by contrast, corresponds to increased winter precipitation, which typically occurs before the main glacier melt season; during this period, the snow cover also protects the glacier surface from direct exposure (Lutz et al., 2014; Pritchard, 2019), delaying melt onset and stabilizing runoff, consistent with a strengthening

direct coupling between snowmelt and discharge. However, our finding of an increased causal impact of snowmelt on river discharge is partially contradictory to the findings of Adnan et al. (2022); Ali et al. (2023); Adnan et al. (2024); Chandel and Ghosh (2021), which however all were conducted in the mountainous parts of the basin. It is also to note that Immerzeel et al. (2015) found that precipitation in high altitudes in the Himalayas is systematically underestimated in most models or gridded precipitation products. Furthermore there is also evidence, that the earlier snowmelt influences the spring runoff in the Indus basin, which in turn supports our findings of an increased causal impact of snowmelt on river discharge Wang et al. (2025); Hasson et al. (2017); Sharif et al. (2013); Guo et al. (2025). Therefore, our findings can be reasonably aligned with existing literature. Given indications of earlier snowmelt onset and an overall increase in snowfall, it appears possible that snowmelt has become relatively more important for basin-wide streamflow generation, although its overall role likely remains secondary to glacier melt.

4.1.3 Cross-basin synthesis and broader implications

Across the six exemplary basins, the magnitude of the snowmelt anomaly increased in all cases, though only significantly in the Colorado, while the resulting coupling strength of discharge to snowmelt diverged by basin type: it decreased in the Mackenzie, Colorado, Danube, and Po, the basins with mountain headwaters feeding arid or temperate lowlands (significantly in the Mackenzie and Colorado), while it increased in the Yenisey and the Indus, the two basins most strongly impacted by permafrost and by extensive glaciation, respectively (significantly in the Indus). For rain, the coupling strength of discharge decreased in five of the six basins (significantly in the Mackenzie and the Indus), with the Po as the sole exception, where it increased significantly alongside a significant increase in the rainfall anomaly. This indicates that the increasing causal role of snowmelt and rain observed across most exemplary basins is, in the majority of cases, driven primarily by growing anomalies in the trigger variables themselves rather than by a systematically strengthening coupling between these variables and discharge. A stronger direct coupling coincides with the anomaly increase in the most strongly cryosphere-dominated of the exemplary basins for snowmelt, and in the Po for rain.

Finally, we can conclude that our results support the qualitative examination for the exemplary basins and align well with the ~~existing body of knowledge~~current state of research. However, it is important to acknowledge that studies verifying the relative influence of snowmelt on river discharge, particularly at our spatial and temporal scales, remain scarce. As a result, our qualitative analysis relies more on indicative findings and approximations than on direct empirical evidence. It is worth noting that although our primary focus is on snowmelt and rain, glacier melt plays a crucial role in certain hydrological systems. We included glacier melt in our analysis to account for its presence, but we did not compute its causal effects. Therefore, glacier melt remains a source of uncertainty when explaining the causal effects of snowmelt and rain. This uncertainty may influence the interpretation of results in basins where glaciers are present. A similar challenge applies to human influences. Currently, there is no comprehensive global dataset quantifying human impacts on hydrological regimes. For this reason, we chose not to include human influences in our setup, even though they can have a considerable effect on certain variables. For example, irrigation in agriculture appears to alter groundwater signals and seasonality in some regions (Carlson et al., 2025; Hall et al., 2024). Similarly, thawing permafrost dynamics remain a major source of uncertainty in especially arctic regions Wang et al.

(2021). Despite these complexities in the explainability of our findings, our results focusing on snowmelt and rain remain valuable, especially given the prevailing consensus that declining snow water equivalent trends in the Northern Hemisphere lead to faster and earlier melt. These changes, combined with more erratic precipitation patterns and prolonged drought periods, make snow increasingly important as a water storage resource. This is particularly relevant in ~~22~~ 38 basins where our method detected an increasing trend in the causal effect of snowmelt on river discharge, even though both snow water equivalent and river discharge showed declining trends. Such regions warrant special attention from researchers and policymakers alike, as regional water availability appears increasingly dependent on snow as a diminishing resource.

Our research also shows that the causal effect of snowmelt on river discharge, as examined in this study, can add a new relative dimension to snow hydrology, which is linked, but not the same, as sole snow dominance. Therefore, snow dominance can decline in a certain region, while the causal effect, and thus the relative impact is increasing, as it quantifies the influence of snowmelt on river discharge as is carried out trough the overall system. For a deeper understanding of the dynamics in a basin, these two measures should therefore be considered together. Moreover, the decomposition into anomaly magnitude and coupling strength presented here adds a further layer to this relative dimension: an increasing causal effect does not necessarily indicate that a system responds more strongly to snowmelt or rain, but may instead reflect that the underlying anomalies themselves have grown. Distinguishing between these two possibilities is relevant for anticipating how basins may respond to further changes in snowmelt and rainfall variability. The qualitative analysis also shows that the method developed here can be applied in various hydrological regimes and climates, and thus can support hydrological studies in a wide range of basins.

4.2 Methodological Discussion

The general intention of this study was to design a causal inference setup capable of capturing the dynamics between snowmelt and river discharge across various regions and extended time periods, enabling comparisons across these spatial and temporal scales. This became necessary as our literature revealed a lack of large-scale studies in the intersection of snow, SWE, and river discharge, using advanced analytical methods. Therefore, all decisions concerning the study design, served the purpose of setting up a resilient and widely applicable method, rather than providing a precise depiction of various local conditions across the study region. Accordingly, the methodological set-up comprises multiple considerations which reflect this optimization towards a broad framework, rather than local accuracy.

Firstly, the selection of data was constrained by spatial and temporal requirements, and while all incorporated datasets are validated and peer-reviewed, they each carry inherent strengths, limitations, and uncertainties. Some datasets also required preprocessing to align with the time-series requirements of ~~the~~ PCMCI+, involving several assumptions that, while necessary and well-supported by literature, may have affected local accuracy. Furthermore, the data ~~was~~ were spatially and temporally aggregated, which affects the ability to capture small scale variations in the data, both spatial and temporal. However, these aggregations were necessary to balance the representation of large spatial and temporal scales with the need for an expedient time lag within the causal inference framework, while minimizing computational demands. Moreover, depicting hydrological context within a scientific approximation is a complex task, which by itself normally already includes various simplifications and assumptions, based on the current knowledge of the topic. For our study, this meant that not all relevant processes could

be incorporated in the system, which is additionally limited by the informative capability of the utilized datasets. However, by focusing on the land surface dynamics of the systems, leaving out all atmospheric processes and land-atmosphere interactions, we could include the key variables for streamflow generation in the studied river basins. ~~However~~Nonetheless, LPCMCI can be considered as an alternative to PCMCI+ for accounting for additional, potentially hidden variables influencing the estimated causal effects. During our development process, we tested the LPCMCI in multiple set-ups, which however did not yield realistic causal effects. One key decision, where we opted to represent local conditions as well as possible was the selection of the intervention in the causal effect estimation. By intervening the system seasonally and per basin, we adequately depict each ~~basins~~ basin's conditions, even though the intervention values are still averaged over the full basin, thus potentially lo~~o~~sing more small scale details. The intervention choice (~~mean vs. zero intervention~~$do(X = \mu)$ vs. $do(X = \mu - \sigma)$) was furthermore driven ~~the initial~~ by the research question regarding the ~~total contribution of~~ sensitivity of river discharge to a typical anomaly in snowmelt and rain~~to river discharge. However, while zero or near zero values of snowmelt and rainfall occur at the two week temporal resolution used in this study, such conditions can be less well represented for specific combinations of season, tau, and period. In these cases, the estimated causal effects are partly informed by model extrapolation rather than being fully constrained by the data. This may affect the~~ , rather than their total contribution. This choice, however, introduces a further limitation to consider when comparing causal effects across variables and basins: since σ is estimated separately for each variable, season, and basin, the magnitude of the ~~estimated contributions and reflects our decision to address the research question of total snowmelt and rainfall contribution to river discharge~~intervention itself varies accordingly. A low causal effect can therefore either indicate a genuinely weak coupling between the trigger variable and discharge, or simply reflect a comparatively small typical anomaly (σ) of the trigger variable in that basin, rather than a weak underlying sensitivity of discharge to it. Consequently, absolute causal effect magnitudes should not be directly compared between variables (e.g. snowmelt vs. rain) or between basins without considering the underlying variability of the respective trigger variable.

Besides the various decisions towards better comparability over the depiction of local mechanisms, the development process was also characterized by the balance between enabling ~~the~~ PCMCI+ to detect effects, and managing the computational demand. The causal inference requires a certain data sample to reliably detect causal effects for a system (Kathpalia et al. (2022)), therefore the sample used to calculate the causal effects needed to be chosen adequately, but in a fashion that within the moving window approach, the computational demand lies within the possibilities of our available infrastructure. The moving window approach itself, which was superimposed on to the causal inference framework, adds certain challenges, mainly concerning the yearly averaging, the years on the temporal edges of the time-series are underrepresented, and are thus susceptible to outliers. As most of the calculated averages used for the trend derivation rely on a broad sample, we refrained from clipping the time-series or introducing shorter additional windows at the edges of the time-series. However, this is one reason why we present trends and not absolute values in this study. Another reason is because absolute values of causal effects are generally dependent on how well the methodical setup recognizes them within the data, which might not always represent the reality. Another sign pointing to this circumstance is that for rain, the ~~relationship~~ link between trigger and target variable

was found more often than for snowmelt. This ~~might be attributed to the signal, which, for rain is nearly detectable all year round. In contrast, snowmelt signal for only occurs in spring and early summer, and is thus detectable in less data points~~reflects a difference in effective sample size between the two signals rather than a shortcoming of the causal inference framework itself: rain occurs throughout the year and yields up to 26 biweekly data points per year, whereas snowmelt occurs only during a limited period of the year, yielding approximately 4-8 biweekly data points per year per basin. This smaller effective sample size reduces the statistical power to detect causal links for snowmelt compared to rain. As this limitation arises from the physical nature of the variables themselves, any causal inference method informed by the data would face the same constraint. We note that where PCMCI+ does not detect a link for a given basin and period, the causal effect estimation returns zero. This may in part reflect the limited effective sample size of the snowmelt signal rather than a genuine absence of a causal relationship.

The presented results are all a ratio of the causal effect to the mean discharge in a certain basin, thus showing a relative change within a basin, which is less dependent ~~of~~ on the ability of recognition within the data by ~~the~~ PCMCI. Within basins the analyzed performance metrics (see section 3.5) show that the yearly values fluctuate on an acceptable level, and the trend derivation thus can be regarded as robust. Also by fitting Theil-Sen slopes we additionally mitigate against any kind of fluctuation within the results, adding to the resilience of the trend statements.

Nevertheless, despite the Theil-Sen method being more robust concerning outliers, it is still a linear fitting method, and thus only remains valid under the assumption of a linear trend. Therefore, for causal and variable trends, we classified the trends by the sign of the slope regardless of the gradient. This was necessary to enable a comprehensive comparison of the method among the basins, and a possibility to categorize them. It, however, might suggest that conditions in a basin ~~being~~ are more severe or extreme, ~~then~~ than they are if one considers the actual data. It~~however~~ , however, also became an inevitable step, to avoid a multitude of potential additional categorizations, which ~~aggravates~~ would complicate an expedient comparison. However, it also underscores the need for a thorough analysis of basin-specific data, as exemplified in Section 3.4 for select basins, to inform qualified statements about the unique circumstances within a given basin.

Generally, as shown in the analysis of exemplary basins in section 3.4, the estimation of causal effect serves as a valuable measure for understanding hydrological dynamics that cannot be captured by individual variables alone. The causal effect can support the determination of certain dynamics and narrowing down unknown developments. However, ~~the PCMCIis calculated~~ PCMCI+ is run per basin, and thus referenced to the corresponding basin discharge, which limits the comparability among basins generally. Because of this, but also given the complexities in detecting effects based on sample size, we recommend using the causal effects computed in this study only to assess relative changes, and as a complementary rather than standalone measure when examining snow-hydrological systems in a given study region.

The use of trends as indication of relative change is additionally supported by the statistical metrics presented in section 3.5. The analysis of the dispersion of the calculated causal effects shows that significant portions of the dispersion are due to the trend itself and the small sample size at the ends of the time series. For a predominant majority of the basins, the trend-corrected dispersion falls within a suitable range for this analysis. Considering that with the Theil-Sen estimator, we used a fitting method which is robust against outliers, we regard the use of trends and thus relative changes as justified.

To conclude, we acknowledge the simplifications and compromises inherent in our study. Our results must be interpreted within the context of individual basins, regional climate dynamics, and broader continental influences. It should be noted that, with the current setup, the results reflect the method's ability to identify causal structures in the data, which may not always translate directly into absolute real world effect magnitudes. Nonetheless, this study introduces a novel, data-driven approach to snow-hydrology that extends beyond conventional statistical measures and small-scale applications. The method has demonstrated adequate responses in plausibility tests and, while still experimental, provides a foundation for future research, both methodologically and in more localized contexts. Despite the challenges of estimating causal effects in snow-hydrology, our findings demonstrate the potential of this approach to complement established methodologies and advance the understanding of hydrological systems.

5 Conclusion

Snowmelt is a crucial contributor to river discharge in various regions on the Northern Hemisphere. It sustains over 1.5 billion people as a societal water supplier, supports key industries like agriculture and hydropower, and impacts regional ecosystems. Due to climate change, snow water equivalent (SWE) is declining, reducing snow-based water availability. A review of large-scale SWE studies reveals that the relationship between SWE and river discharge has rarely been examined beyond basic statistical measures, which cannot capture the complexity of hydrological regimes. To address this gap, we developed a causal inference approach based on Peter and Clark Momentary Conditional Independence Plus (PCMCI+). PCMCI+ performs causal discovery and detects a network of causal links within a multivariate system. ~~The~~ PCMCI+ is followed by a causal effect estimation which quantifies the effect of a trigger variable onto a target variable within the same system. Our system includes river discharge, snowmelt (defined as SWE depletion), rain, glacier runoff, baseflow flux, soil moisture, evapotranspiration, temperature, and the date as a deterministic time variable, with lags of up to six months. Causal effects of snowmelt and rain on river discharge were estimated applying a moving 20-year window to the 1980–2022 time series. The resulting effects were summed and then divided by the period's mean river discharge and finally averaged by year. The yearly averages were used to quantify trends with a Theil-Sen estimator. We present these causal effect trends for 119 Northern Hemisphere basins, alongside Theil-Sen trends for individual variables. In addition, we examine six representative basins to illustrate differing hydrological and geographic dynamics. Based on these results, several overarching conclusions can be drawn:

- Our trend analysis confirmed a decreasing trend for SWE in a majority of the examined basins (94/119).
- Also, the trends for river discharge (79/119) and rain (71/119) in the catchments are predominantly negative.
- Looking at patterns among these discharge, rain, and SWE trends, two major dynamics become apparent. Firstly, in all Arctic basins (except Yenisey) the SWE trend is negative while the rain trend is positive. Secondly in lower latitudes, the basins where all these trends are negative make up the largest share of the basins (51/102).
- Of all basins where a causal effect for snowmelt on river discharge was detected, ~~32~~ 64 of 73 (~~43~~88%) showed an increasing trend. For the causal effect of rain on river discharge ~~57 of 117 (48.7~~97 of 114 (85%) had an increasing trend.

- For the causal effect of snowmelt on river discharge, the largest increasing trend was found in the ~~Dnieper basin (Ukraine, Belarus, Russia~~Columbia basin (USA/Canada), the ~~most decreasing trend at the Mediterranean Sea east coast (Türkyie, Lebanon, Syria, Israel, Jordan, Palestine)~~steepest decrease was found in the Ziya He Interior basin in China.
- Correspondingly the largest increasing trend was seen in the ~~Hamun-e Mashkid basin (Iran)~~Baltic Sea East Coast, the steepest decreasing trend in the ~~Rio Grande (USA/Mexico~~Lena basin (Russia).
- No effects could be found using correlation of the causal effect trends against latitude, mountainous portion of the basin, or snow dominance.
- In ~~22 basins, 20 of which are located in Eurasia,~~ 40 basins, our method detected an increasing causal effect of snowmelt on river discharge, despite declining trends in SWE and river discharge. These areas are critical for researchers and policymakers, as they indicate water availability is increasingly reliant on snow, despite it being a diminishing resource. This can have various implications for funding decisions in water management, conservation, and research.
- ~~Looking at~~ For the six exemplary basins (Mackenzie, Colorado, Danube, Po, Yenisey, and Indus)~~showed that partly similar dynamics appear in the Danube and Colorado basin, while Poand Indus, despite sharing geographical similarities to Danube and Colorado, stand alone in their dynamics. In the Arctic, Yenisey and Mackenzie show opposite causal trends~~, decomposing the causal effect trends into anomaly magnitude and coupling strength revealed a consistent pattern among the four basins with mountain headwaters feeding arid or temperate lowlands (Mackenzie, Colorado, Danube, Po): in all four, the coupling strength between snowmelt and discharge decreased despite a growing snowmelt anomaly. The Yenisey and the Indus, in contrast, are shaped most strongly by permafrost and extensive glaciation, respectively, and both showed an increasing coupling strength for snowmelt. For rain, coupling strength decreased in five of the six basins, with the Danube as the sole exception.
- ~~It is observed that the~~ The causal effect of snowmelton river discharge can increase despite decreasing SWE trends, and ~~also despite increasing rain and rain causal effect~~ even despite increasing trends in rain and in the causal effect of rain on river discharge~~trends. This, in the scope of our analysis, seems to be due to changed seasonalities, and especially increased intra-annual variability of precipitation, thus that in drought periods the stored SWE has an increased influence, as precipitation during summer and autumn is occurring less~~. Decomposing the causal effect trend indicates that, across most basins, this increase is primarily driven by a growing magnitude of the snowmelt anomaly itself, rather than by an increased coupling between snowmelt and discharge.
- Dispersion metrics (Coefficient of Variation; CV, and trend-corrected CV, Trend-CV) show that generally our method is suited for trend derivation, especially as a significant portion of the dispersion is due to the ends of the time series and their reduced sample size in the moving window approach, as well as the trend itself.

Although our method did not detect causal effects, and therefore trends, in all basins, and the effect size depends on the selected random forest estimator, it advances large-scale snow hydrology by capturing the complexity of hydrological regimes beyond conventional statistical approaches. To enable large-scale comparison, we made several methodological decisions that prioritized comparability over local accuracy. While this allowed for the analysis presented in this study, it limits the resolution

of local dynamics within basins. Despite these limitations, we demonstrated that causal effects, even within an experimental framework, are a suitable means of assessing relative changes in the importance of snowmelt, which does not necessarily align with snow dominance itself. Within this experimental framework, causal inference can add an additional layer to existing hydrological analyses, with further methodological refinements potentially expanding its applicability in future research.

Data availability. All data used in this study are publicly available. The datasets and their access details are listed in the manuscript and referenced with persistent identifiers (DOIs) in the reference list.

Code availability. The analysis code used in this study is available on ~~reasonable~~ request from the corresponding author.

Appendix A: Hydrological System for Causal Discovery

Figure A1 expands on the hydrological links described in Section 2.5.1. These links reflect established hydrological and atmospheric relationships and constrain the search space of PCMCI+ without imposing fixed causal connections. For example, the evapotranspiration variable used in this study intentionally excludes open-water evaporation, which operates directly at the river surface rather than through terrestrial pathways, and snow sublimation, whose inclusion would contradict the snowmelt definition used in this study (Section 2.3.1). Within this definition, evapotranspiration influences river discharge only indirectly, through soil moisture depletion, which is explicitly included as a mediating variable in the causal graph; no direct link from evapotranspiration to river discharge is therefore specified.

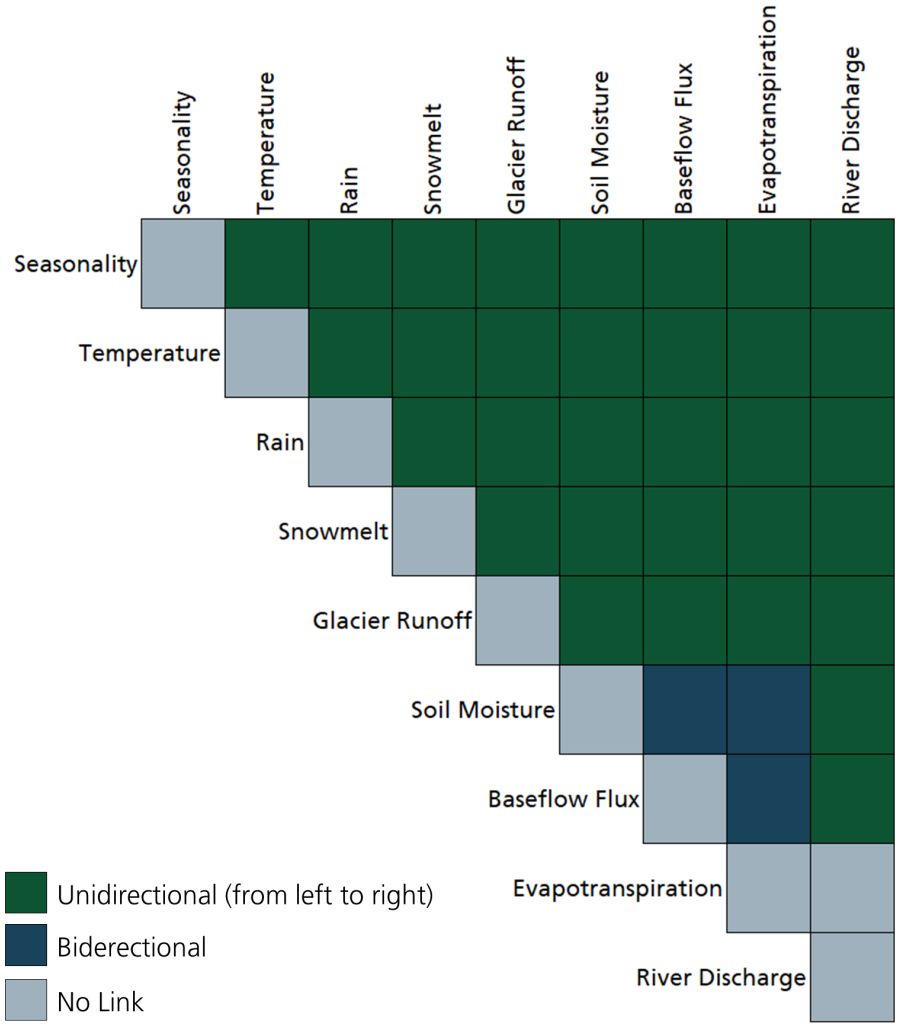


Figure A1. The assumed potential links between the variables used in the causal discovery phase. Evapotranspiration is linked to river discharge only indirectly via soil moisture; open-water evaporation and snow sublimation are excluded from the evapotranspiration definition.

Appendix B: Full Results~~Heatmap~~

This appendix provides the complete results shown as maps in section 3, presented here as tables with corresponding colors. The figures are grouped by continent.

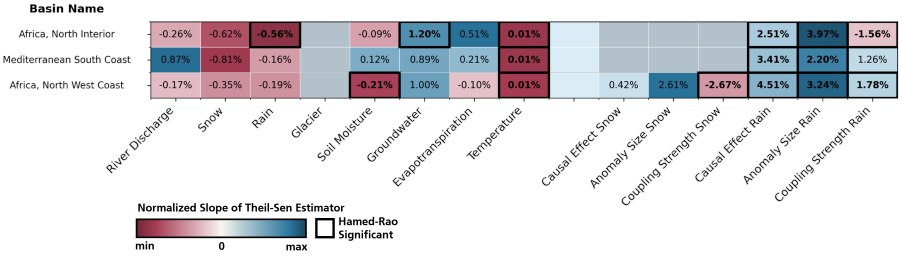


Figure B1. Relative variable trend slopes for all African basins normalized with the basin mean per variable (left) and causal effect trend slopes as absolute values (ratio of causal effect to mean discharge) as well as relative values, normalized with the basin mean (right). The colorscale for the temperature is inverted

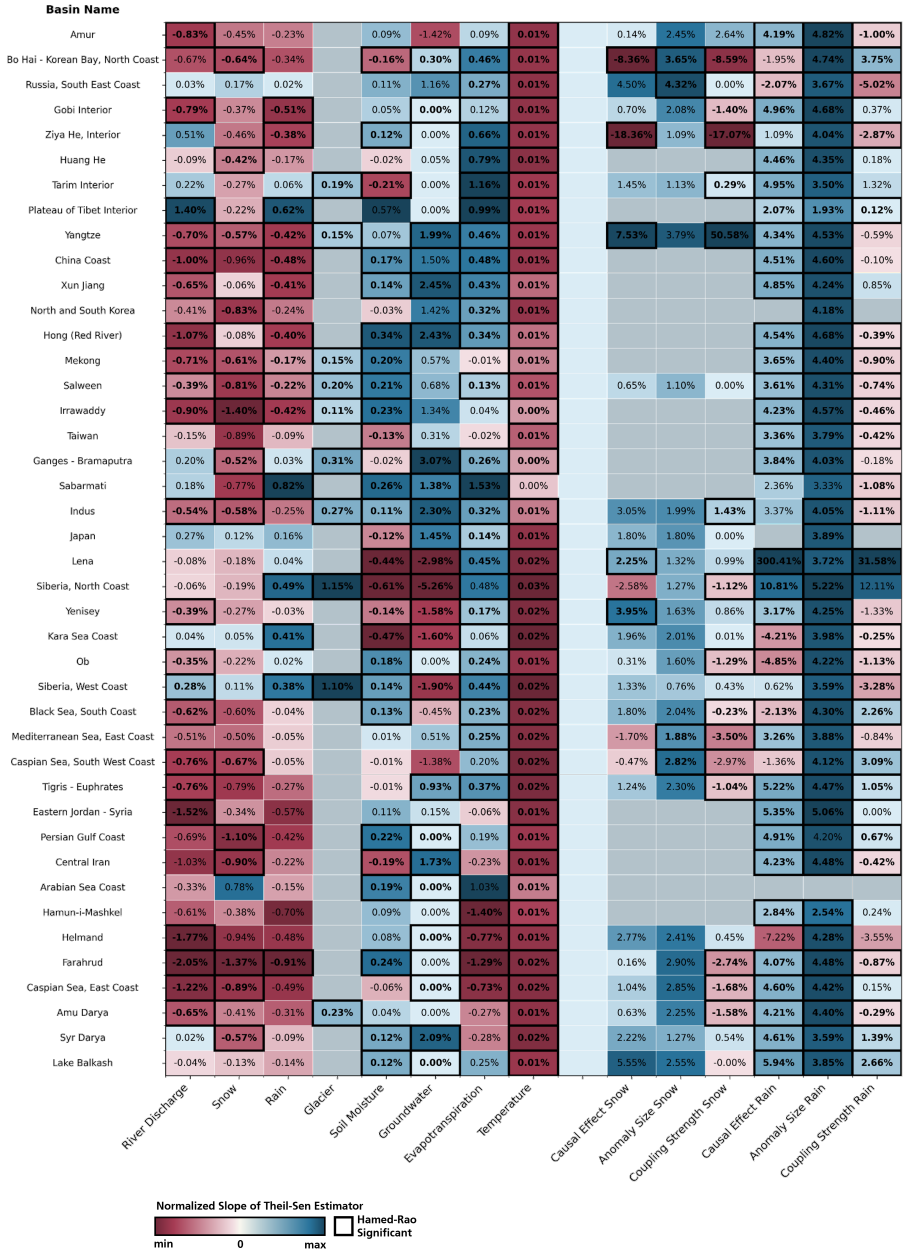


Figure B2. Relative variable trend slopes for all Asian basins normalized with the basin mean per variable (left) and causal effect trend slopes as absolute values (ratio of causal effect to mean discharge) as well as relative values, normalized with the basin mean (right). The colorscale for the temperature is inverted

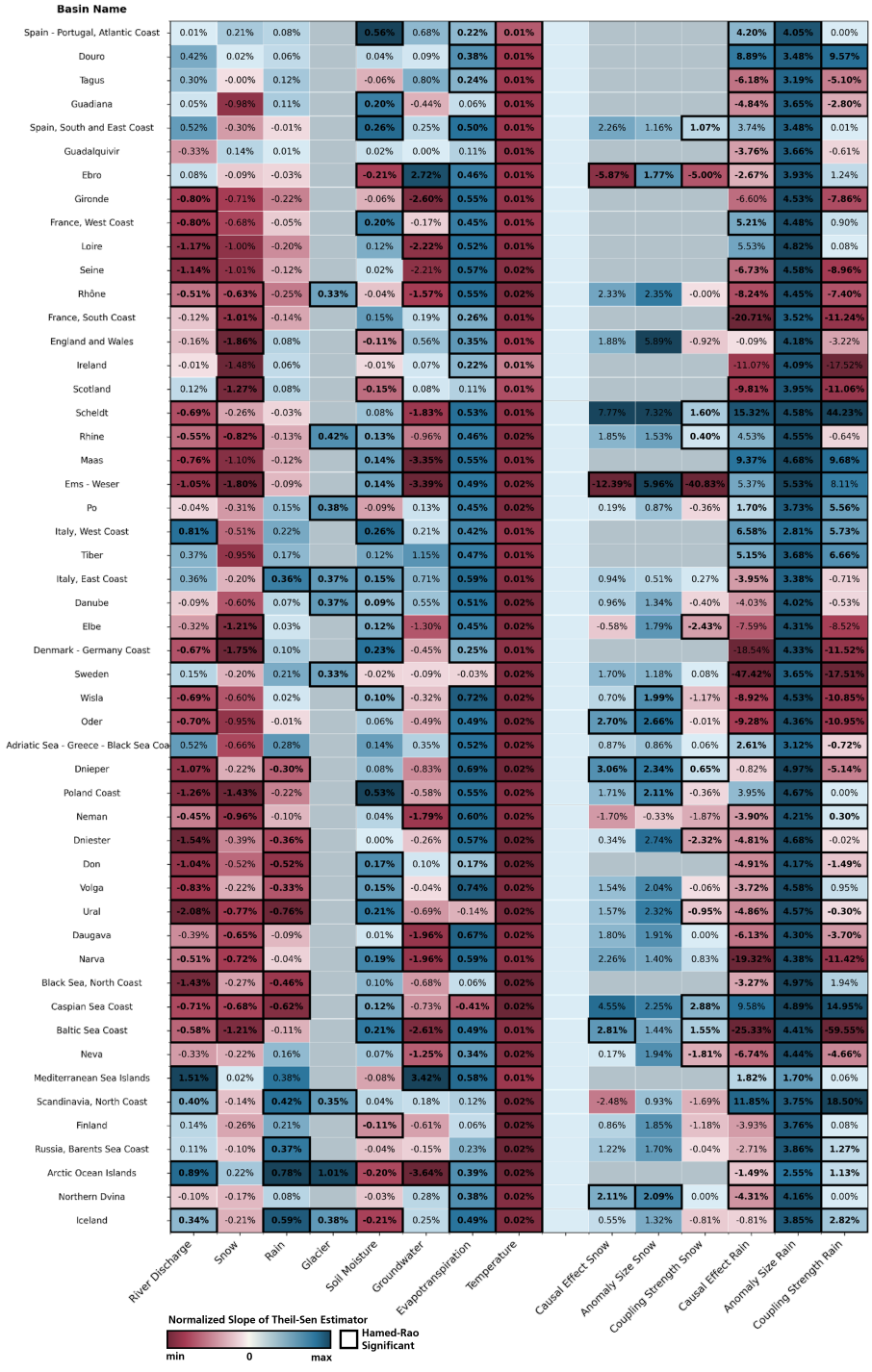


Figure B3. Relative variable trend slopes for all European basins normalized with the basin mean per variable (left) and causal effect trend slopes as absolute values (ratio of causal effect to mean discharge) as well as relative values, normalized with the basin mean (right). The colorscale for the temperature is inverted

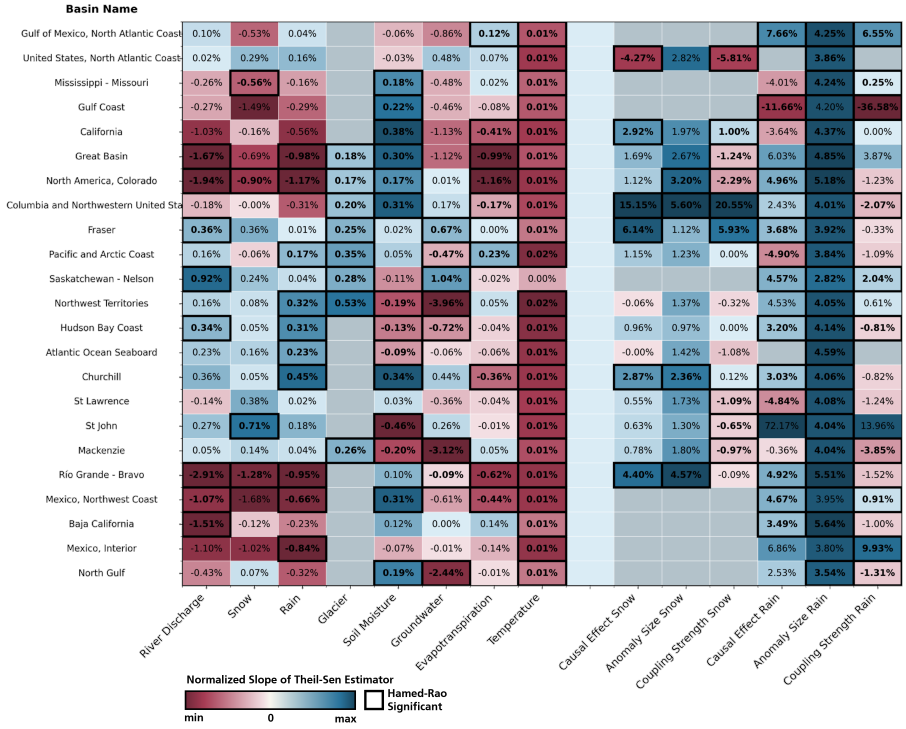


Figure B4. Relative variable trend slopes for all North American basins normalized with the basin mean per variable (left) and causal effect trend slopes as absolute values (ratio of causal effect to mean discharge) as well as relative values, normalized with the basin mean (right). The colorscale for the temperature is inverted

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