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The seasonal origins of streamwater in Switzerland

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Key Points:

- We tested whether summer or winter precipitation is over-represented in streamflow relative to its proportion of total precipitation
- Oxygen-18 ratios in streams indicate that similar fractions of summer and winter precipitation become discharge in Switzerland
- Inter-seasonal storage can explain why the seasonal partitioning of precipitation can differ substantially from the seasonal water balance.

Abstract

Quantifying the relative contributions of winter versus summer precipitation to streamflow may be important for understanding water-resource sensitivity to precipitation variability. Here we compare volume-weighted mean $\delta^{18}O$ values in precipitation and streamflow for 12 catchments in Switzerland, to determine whether summer or winter precipitation is over-represented in streamflow, relative to its proportion of total precipitation. Similarities between precipitation and streamflow weighted-mean $\delta^{18}O$ values indicate that roughly equal fractions of summer and winter precipitation supply streams in Switzerland. These results, together with mass conservation, suggest that similar fractions of summer and winter precipitation supply evapotranspiration. These findings contrast with the assumption that because summer precipitation falls when transpiration rates and evaporative demand are high, it should be under-represented in streamflow and over-represented in evapotranspiration. This contrast between seasonal water-balance variations and the partitioning of seasonal precipitation into runoff and evapotranspiration demonstrates substantial inter-seasonal carryover of precipitation in storages that supply evapotranspiration.

Plain Language Summary

Precipitation inputs often greatly exceed streamflow outputs during the summer in seasonal climates because evapotranspiration rates are much higher in summer than in winter. Such seasonal water balance variations often lead to the expectation that smaller proportions of summer precipitation and larger proportions of winter precipitation eventually become streamflow. We tested which seasons' precipitation was over-represented in streamflow, relative to their proportions of total precipitation. We did this using the stable isotope ratios of precipitation – which are distinctly heavier in summer than in winter – and streamflow in 12 streams in Switzerland. We found that the volume-weighted averages of precipitation and streamflow were isotopically similar, implying that neither season is over-represented in streamflow. Thus, the fraction of summer precipitation that becomes streamflow roughly equals the fraction of winter precipitation that becomes streamflow. Our results potentially suggest that streamflow and evapotranspiration, including the use of water by plants during growing seasons, may both be sensitive to fluctuations in summer and winter precipitation.

1 Introduction

Differences between the isotopic signatures of mean streamflow and precipitation can reflect the relative amounts of summer versus winter precipitation in streamflow. Isotope ratios in precipitation commonly exhibit strong seasonal cycles, especially outside of the tropics, with isotopically heavier precipitation in summer and lighter in winter (Allen et al., 2019a; Bowen, 2008). Past studies have used seasonal cycles in precipitation isotope ratios to distinguish between the relative contributions of summer versus winter precipitation in aquifers (e.g., as synthesized by Jasechko, 2019; Jasechko et al., 2014) or plant xylem (Allen et al., 2019b; Martin et al., 2018). Here we use seasonal precipitation isotope cycles to determine the relative contributions of summer and winter precipitation to streamflow, and thus to infer how precipitation from different seasons is partitioned into streamflow versus evapotranspiration. Seasonal water balances alone cannot provide this information because significant volumes of precipitation that fall in one season can potentially be stored in the catchment and become streamflow or evapotranspiration in other seasons. Thus quantifying the seasonal partitioning of precipitation into streamflow and evapotranspiration requires tracers.

We analyze the seasonal origins of precipitation that becomes discharge in 12 catchments in Switzerland. We compare the annual volume-weighted mean δ^{18}O of streamflow ($\delta_{\bar{Q}}$) to that of precipitation ($\delta_{\bar{P}}$), to determine whether inputs of summer versus winter precipitation are over-represented in discharge, relative to their proportions of total precipitation. Our partitioning analysis differs from previous studies focusing on how streamflow is composed of waters of different ages (Rinaldo et al., 2015; Sprenger et al., 2019). Our analysis, by contrast, asks what are the relative proportions of each season's precipitation that eventually become discharge (Q), which also provides insights into the relative proportions supplying evapotranspiration (ET) instead. Characterizing this precipitation partitioning is crucial for understanding how waters mix and recharge different hydrologic storages that ultimately serve distinct functions (e.g., supporting plants versus supplying rivers). We test the null hypothesis that the fraction of winter precipitation that eventually becomes streamflow is larger than the fraction of summer precipitation that eventually becomes streamflow. This hypothesis would hold true in Switzerland – where ET in summer is a larger fraction of summer precipitation than is ET in winter of winter precipitation (Spreafico and Weingartner, 2005) – if there were no inter-seasonal carryover of precipitation in storages that potentially supply ET. In that scenario, seasonal variations in the partitioning of precipitation into Q would match variations in seasonal water-balance surpluses ($P-ET = Q$). The alternative hypothesis is that substantial precipitation carryover across seasons (e.g., in snowpacks or in soils) supplies evapotranspiration, such that the fraction of summer precipitation that eventually becomes discharge equals or exceeds the fraction of winter precipitation that eventually becomes discharge.

2 Materials and Methods

2.1 The seasonal origin index

Here we adapt the seasonal origin index (SOI) introduced by Allen et al., (2019b) to test whether winter or summer precipitation is over-represented in annual streamflow. This index quantifies the isotopic deviation of annual average discharge from annual average precipitation, and then scales that deviation by the strength of the seasonal isotope cycle, yielding a unitless seasonal origin index (SOI):

$$\mathrm{SOI}_{\bar{Q}} = \begin{cases} \frac{\delta_{\bar{Q}} - \delta_{\bar{P}}}{\delta_{P_s} - \delta_{\bar{P}}}, \text{ if } \delta_{\bar{Q}} > \delta_{\bar{P}} \\ \frac{\delta_{\bar{Q}} - \delta_{\bar{P}}}{\delta_{\bar{P}} - \delta_{P_w}}, \text{ if } \delta_{\bar{Q}} < \delta_{\bar{P}} \end{cases} . \qquad (1)$$

In Eq. 1, δ_{Pw}, δ_{Ps}, and $\delta_{\overline{P}}$ are the δ^{18}O values of typical mid-winter, typical mid-summer, and volume-weighted annual precipitation at each study site, and $\delta_{\overline{Q}}$ is the annual volume-weighted mean streamflow δ^{18}O. The values of δ_{Pw} and δ_{Ps} are defined as the trough and peak of a sinusoid representing the seasonal precipitation isotope cycle in a given location or region. This analysis is only useful in regions where the seasonal isotope amplitude is large enough that δ_{Pw} and δ_{Ps} are consistently and substantially different (although other climate factors can influence the interpretation of SOI values, as discussed in section 3.2 and the Supporting Information). The SOI was previously used to identify whether precipitation inputs from summer or winter are over-represented (relative to their volumes) in tree xylem water (Allen et al., 2019b). Here we focus on the SOI of weighted-mean streamflow ($SOI_{\overline{Q}}$), although we also calculate the SOI of individual streamflow samples (SOI_q) by replacing $\delta_{\overline{Q}}$ in Eq. 1 with their individual isotope ratios (δ_q). One could also adapt this approach to estimate the SOI of cumulative evaporation ($SOI_{\overline{E}}$), cumulative transpiration ($SOI_{\overline{T}}$), and cumulative evapotranspiration ($SOI_{\overline{ET}}$) by replacing $\delta_{\overline{Q}}$ in Eq. 1 with the (measured or hypothetical) average δ^{18}O of the corresponding hydrological flux.

The SOI can be used to characterize whether summer or winter precipitation is over- or under-represented in streamflow across sites with different seasonal precipitation volumes and isotope cycles. For example, a positive $SOI_{\overline{Q}}$ means that a larger fraction of summer precipitation becomes streamflow compared to the fraction of total precipitation that becomes streamflow. By comparing to volume-weighted-mean precipitation, SOI values are adjusted for potential differences in the amounts of precipitation falling in summers versus winters. SOI values should be near -1.0 for water samples composed of typical mid-winter precipitation, and near 1.0 for water samples composed of typical mid-summer precipitation. $SOI_{\overline{Q}}$ values near zero imply that similar fractions of summer and winter precipitation become streamflow (or, hypothetically, that the contributions from summer and winter are both small compared to spring and autumn precipitation, with isotope values close to the annual average).

In climates where precipitation falls evenly throughout the year, $SOI_{\overline{Q}}=0$ not only indicates that similar fractions of summer and winter precipitation become streamflow, it also indicates that streamflow is composed of a roughly even mixture of summer and winter precipitation. In Switzerland, where slightly more precipitation falls in summer than in winter (section 2.2), $SOI_{\overline{Q}}=0$ implies that mean streamflow is composed of slightly more summer precipitation than winter precipitation. In a climate where nearly all precipitation falls in winter, $SOI_{\overline{Q}}=0$ implies that streamflow is mostly composed of winter precipitation; furthermore, it may be difficult to interpret negative $SOI_{\overline{Q}}$ values in that scenario because δ_{Pw} and $\delta_{\overline{P}}$ would be similar and thus small variations in $\delta_{\overline{Q}}$ could yield drastically different $SOI_{\overline{Q}}$ values. By definition, the over-expression of summer precipitation relative to its proportion of total precipitation always yields positive SOI values, and the over-expression of winter precipitation always yields negative SOI values; however, the relative magnitudes and uncertainties of positive and negative SOI values depend on the seasonality of precipitation volumes (section 3.2).

2.2 Catchment characteristics

We use measurements from 12 Swiss catchments (Fig. S1), comprising all of the sites previously analyzed by Seeger and Weiler (2014) and von Freyberg et al. (2018) that have at least four years of streamwater isotope measurements. Catchment areas ranged from 0.7 to 261 km^2, with mean elevations from 584 to 2369 m a.s.l (Table S1). These catchments are mostly located in the northern Alps and the Swiss Plateau, and are mostly underlain by sedimentary rocks and unconsolidated sediments. Forest cover varies by site, ranging from 3% (in the highest elevation catchment) to 82% (in a wet mid-elevation catchment; Table S1). Agriculture, grassland and forests are found at elevations up to approximately 2000 m, above which the ground cover is mostly meadow (and some rock, snow or ice). The effects of these catchment characteristics on streamflow transit times and runoff processes have been described in previous studies (von Freyberg et al., 2018; Seeger and Weiler, 2014).

Switzerland’s climates are largely humid to temperate continental, although the mountains cause climatic heterogeneities that include relatively drier regions. Our sites include catchments that lie in some of Switzerland's wetter regions (e.g., the northern pre-Alps) and drier regions (i.e., valleys in the eastern Alps and the northern Swiss plateau; Fig. S1). While catchment annual precipitation ranges from 1081 to 1853 mm/y in these catchments (2000-to-2015 means), potential evapotranspiration exceeds precipitation in summer in the drier regions (Spreafico and Weingartner, 2005). Precipitation amounts are mildly seasonal; averaged across the study catchments, 59.5% of precipitation falls in April-September and 40.5% falls in October-March. The catchments comprise snow-dominated, rain-dominated and hybrid climates (Staudinger et al., 2017). In the low-elevation, rain-dominated catchments, snow may sometimes fall in winter but snowpacks are ephemeral and do not accumulate.

2.3 Precipitation isotope data

As described in Eq. 1, SOI calculations require annual volume-weighted means and typical seasonal values of precipitation δ^{18}O, integrated across each catchment. Monthly catchment-integrated, cumulative precipitation δ^{18}O was calculated using the method described in the Supplement to von Freyberg et al. (2018). In brief, monthly gridded (200 m) isotope values were derived from a combined multiple regression (of latitude, longitude, and elevation) and kriging model that was fitted to precipitation isotope measurements from monitoring stations in Switzerland and Germany (similar to the method tested in Allen et al., 2018). The multiple-regression model fitted sine curves to monthly isotope data, and the kriging step adjusted for monthly deviations from the sine curves to yield monthly isotope values (for which the mean absolute error was 1.3‰). The monthly values were used in calculating the volume-weighted mean, $\delta_{\bar{P}}$. The estimated seasonal isotope cycles were used to calculate δ_{P_w} and δ_{P_s} as sine-curve offsets (i.e., the value around which the curve oscillates) ± amplitudes. Thus the ‘summer’ and ‘winter’ seasons are defined by the fitted sine curves themselves, which peak in mid-July and are lowest in mid-January in Switzerland (Allen et al., 2018). Summer versus winter seasons may roughly correspond to liquid (rain) versus solid (snow) precipitation in the higher-elevation catchments, but not at lower elevations where rainfall occurs regularly in winter.

Gridded precipitation amount data for 100-m elevation bands of each catchment were provided by the PREVAH modelling project (Viviroli et al., 2009; Viviroli et al., 2009), based on interpolations of measurements by the Swiss national meteorological service (MeteoSwiss, Zurich, Switzerland). These were used to weight the gridded precipitation isotope data, yielding catchment-integrated, amount-weighted, monthly precipitation δ^{18}O values. These precipitation isotope values were calculated for each catchment for the years 2010 through 2015 and aggregated for complete years that matched those represented in the streamflow isotope datasets (described in section 2.4). The precipitation data were aggregated to yield a single catchment- and time-integrated estimate of cumulative precipitation δ^{18}O ($\delta_{\bar{P}}$) for each catchment. Standard errors of $\delta_{\bar{P}}$ were calculated using individual-year δ^{18}O means (Table S1).

2.4 Streamflow data

Streamwater grab samples were collected at approximately two-to-four-week intervals at the 12 catchments between mid-2010 and late 2015. Oxygen isotope ratios were measured with Picarro isotope analyzers (L-2120i and L-2130i; Picarro Inc., Santa Clara, CA, USA, which have manufacturer-reported accuracies of 0.16‰ for δ^{18}O and 0.6‰ for δ^{2}H) at the University of Freiburg im Breisgau, Germany. Values are reported here as δ^{18}O values relative to the VSMOW standard.

Daily-mean discharge data were matched to the streamflow grab samples. Discharge measurements for the Erlenbach, Vogelbach and Lümpenenbach catchments were provided by the Swiss Federal Research Institute WSL (Birmensdorf, Switzerland). Discharge measurements for the other nine catchments were provided by the Swiss Federal Office for the Environment.

The streamflow isotope values are unlikely to have been substantially altered by evaporative fractionation. The streamflow samples closely follow meteoric water lines of slope$\approx$8 (Craig, 1961; see Fig. S2), consistent with previous suggestions that the waters that become evaporated in terrestrial environments contribute little to streamflow because they are instead held in soils and used by plants (e.g., Brooks et al., 2010), or because they evaporate completely (e.g., with interception loss; Allen et al., 2017; Coenders-Gerrits et al., 2014). In either case, the net result is that strongly fractionated isotope values are rarely observed in streamflow from humid landscapes.

The datasets were cropped such that four to five years were available after removing sparsely measured (<8 measurements) or unevenly sampled years. To maximize the years of record while eliminating substantial data gaps, these years were not calendar years (1-January through 31-December), but instead complete years from November through the following October. Each data series was discretized into individual years so that metrics of inter-annual variability in weighted-mean streamflow δ^{18}O could be calculated.

Using these data, we calculated volume-weighted means of annual streamflow δ^{18}O ($\delta_{\bar{Q}}$) of each catchment. Note that precipitation $\delta_{\bar{P}}$ was also calculated as a volume-weighted mean but it also represents cumulative precipitation δ^{18}O; alternatively, total monthly streamflow amounts were not collected, so we do not refer to $\delta_{\bar{Q}}$ as cumulative streamflow δ^{18}O. Nonetheless, $\delta_{\bar{Q}}$ should closely approximate cumulative discharge δ^{18}O (as further evaluated in section 3.2), because the grab samples were collected evenly across the seasons and ranges of discharge (Fig. S3; also see Section 3.1).

We used mass balance calculations to infer how observed $\delta_{\bar{Q}}$ and $\mathrm{SOI}_{\bar{Q}}$ values result from the partitioning of summer and winter precipitation into discharge and evapotranspiration (Section 3.2). We used the area-weighted mean annual precipitation across the 12 catchments (1367 mm) and assumed that annual ET is 584 mm, ranging from 0.3 to 2.9 mm day^{-1} from winter to summer, based on hydrologic predictions for regions containing these catchments (Spreafico and Weingartner, 2005).

3 Results and discussion

3.1 Mean streamflow δ^{18}O approximates mean precipitation δ^{18}O

Volume-weighted mean streamflow δ^{18}O ($\delta_{\bar{Q}}$) and cumulative precipitation δ^{18}O ($\delta_{\bar{P}}$) were similar in the study catchments (Fig. 1; see also Fig. S4). Differences of $\delta_{\bar{Q}}$ from $\delta_{\bar{P}}$ ranged from −0.50‰ to 0.35‰ (mean=0.07‰). These differences were all small compared to the seasonal ranges of precipitation δ^{18}O, which were ~4‰ heavier in summer (or lighter in winter) than annual precipitation δ^{18}O (shaded areas in Fig. 1). The corresponding area-weighted mean $\mathrm{SOI}_{\bar{Q}}$ was −0.007±0.016 across the 12 study catchments, demonstrating that at these sites, the fractions of winter and summer precipitation that eventually become streamflow are approximately equal.

The catchments mostly had mean $\mathrm{SOI}_{\bar{Q}}$ values near zero, despite exhibiting widely differing intra-annual patterns in SOI_q calculated for individual streamflow samples (Fig. 2). For example, summer or winter precipitation was often greatly over-represented in streamflow samples from Erlenbach, in contrast to the behavior seen at Dischmabach, Murg, and Langeten (Fig. 2). Such contrasts in short-timescale isotopic variability imply differences in how catchments store, mix, and transport water, damping and delaying the expression of seasonal precipitation δ^{18}O in streamflow, as previously described by von Freyberg et al. (2018). Thus, the similar $\mathrm{SOI}_{\bar{Q}}$ values shown across catchments in Fig. 1 arise despite their diverse transport behaviors, as illustrated in Fig. 2.

Because $\mathrm{SOI}_{\bar{Q}}$ was similar across the catchments, it did not strongly correlate with any catchment characteristics. One might expect snowier catchments to have lower $\mathrm{SOI}_{\bar{Q}}$ (if snowmelt more efficiently reaches streams; e.g., Beria et al., 2018), but $\mathrm{SOI}_{\bar{Q}}$ was not significantly correlated with mean catchment elevation (Fig. S5). Winter precipitation was not over-represented in streamflow in higher-elevation catchments, even though snowmelt in those catchments yielded high discharge rates; this example demonstrates the importance of distinguishing effect-tracking from source-tracking when examining the hydrologic consequences of snowmelt (Weiler et al., 2018). Values of $\mathrm{SOI}_{\bar{Q}}$ were not strongly correlated with the fraction of forest cover (Fig. S5b), or with the timing of the highest and lowest monthly flows (Fig. S5c,d). Ultimately, the most remarkable pattern in these $\mathrm{SOI}_{\bar{Q}}$ values is their consistency across catchments that span a wide range of climates, characteristics and flow regimes.

The similarity between $\delta_{\overline{Q}}$ and $\delta_{\overline{P}}$ (and the resulting $SOI_{\overline{Q}} \approx 0$) is unlikely to result from sampling biases and uncertainties. Annual $\delta_{\overline{Q}}$ and $\delta_{\overline{P}}$ were consistent among years, with cross-catchment mean standard errors of 0.25‰ and 0.40 ‰ among individual years (Fig. 1; Table S1). The resulting SOI standard errors ranged from 0.04 to 0.07. Agreement between the full range of discharge rates and those on streamflow grab-sample days (Fig. S3) provides evidence that we avoided errors associated with inadequately capturing high flows. Even if higher flows were missed, catchments were inconsistent in whether $\delta^{18}O$ values increased or decreased with higher flows (Fig. S6). While the precipitation predictions also have uncertainty, systematic biases are unlikely because the precipitation $\delta^{18}O$ model was fitted to data from Switzerland and southern Germany (across a range of latitudes and elevations that is consistent with the catchments) and thus overestimates of $\delta_{\overline{P}}$ should occur as frequently as underestimates. To understand the consequences of potential snowfall undercatch, which is known to sometimes occur (Fassnacht, 2004), we tested the effects of assuming that winter precipitation amounts were systematically underestimated by 10%: mean $SOI_{\overline{Q}}$ of the 12 catchments would increase from −0.007 to 0.018. If more than 10% of winter precipitation were unaccounted for, $\delta_{\overline{P}}$ would further decrease and $SOI_{\overline{Q}}$ would increase, implying even greater contrast between our findings and the null hypothesis (that more winter precipitation eventually becomes streamflow). If we assumed that summer or winter runoff was systematically underestimated by 10%, mean $SOI_{\overline{Q}}$ values would change by less than 0.001. Thus, the convergence in $SOI_{\overline{Q}}$ values is unlikely to be due to uncertainties.

3.2 Implications for the partitioning of seasonal precipitation into streamflow and evapotranspiration

Across these diverse Swiss catchments, the fraction of summer precipitation that becomes streamflow roughly equals the fraction of winter precipitation that becomes streamflow. This observation suggests that the fraction of summer precipitation that becomes evapotranspired should roughly equal the fraction of winter precipitation that becomes evapotranspired. That is, if $SOI_{\overline{Q}}$ exactly equals 0.0, then so must $SOI_{\overline{ET}}$ because discharge and evapotranspiration jointly close the water balance. If $SOI_{\overline{Q}}$ is positive or negative, then $SOI_{\overline{ET}}$ must be of opposite sign (although not necessarily of equal magnitude; e.g., see Fig. S7). Our inference that $SOI_{\overline{Q}} \approx SOI_{\overline{ET}} \approx 0$ in the Swiss study catchments implies neither that Q (or ET) is composed of equal amounts of summer and winter precipitation, nor that summer (or winter) precipitation is evenly divided between ET and Q. Instead, our data demonstrate that winter and summer precipitation are represented in annual streamflow in roughly equal proportions to their respective shares of total annual precipitation.

For consistency with our previous study of tree xylem water in Switzerland (Allen et al., 2019b), SOI is defined identically here, although using typical mid-winter and mid-summer values for δ_{Pw} and δ_{Ps} limits quantitative inferences about $SOI_{\overline{ET}}$. In very humid climates with $ET \ll Q$, $SOI_{\overline{Q}}$ values that deviate slightly from zero can correspond to $SOI_{\overline{ET}}$ values that deviate substantially more from zero, implying that summer and winter precipitation are not similarly represented in ET. The highest $\mathrm{SOI}_{\overline{Q}}$ value among our sites ($\mathrm{SOI}_{\overline{Q}}$=0.10) comes from a medium-elevation catchment with 1771 mm of annual precipitation (Table S1). At this catchment, Q fluxes are larger than ET fluxes, so the positive $\mathrm{SOI}_{\overline{Q}}$ must be complemented by a negative $\mathrm{SOI}_{\overline{ET}}$ of larger magnitude, implying that winter precipitation is over-represented in ET. The lowest $\mathrm{SOI}_{\overline{Q}}$ value, −0.12, is from a low-elevation catchment with 1314 mm of annual precipitation (Table S1), where Q and ET are probably of similar magnitudes; the negative $\mathrm{SOI}_{\overline{Q}}$ at this site would be offset by a positive $\mathrm{SOI}_{\overline{ET}}$ of roughly equal magnitude. In the three wettest sites where annual precipitation exceeds 1800 mm, $|\mathrm{SOI}_{\overline{ET}}|$ would be larger than $|\mathrm{SOI}_{\overline{Q}}|$, but $|\mathrm{SOI}_{\overline{Q}}|$ values there are zero within error (i.e., <0.05; Table S1).

If we had alternatively defined δ_{Pw} and δ_{Ps} as the weighted-mean precipitation of summer and winter precipitation (e.g., April-September and October-March), we could explicitly calculate $\mathrm{SOI}_{\overline{ET}}$ from $\mathrm{SOI}_{\overline{Q}}$ (Supporting Information Eqs. S1-S13). Using this alternative formulation would aid in inferring $\mathrm{SOI}_{\overline{ET}}$ where $\mathrm{SOI}_{\overline{Q}}\neq 0$ and precipitation amounts are uneven across seasons or Q and ET differ greatly in magnitude. In the present study, however, 8 of our 12 sites have $\mathrm{SOI}_{\overline{Q}}$ within one standard error of zero, and 11 of 12 have $\mathrm{SOI}_{\overline{Q}}$ within two standard errors of zero, making precise calculations unnecessary.

Figure 3 shows the partitioning of summer and winter precipitation into streamflow and evapotranspiration, under three alternative scenarios. Similar scenarios are also explored in Fig. S7 through month-by-month calculations of how hypothetical differences in the partitioning of summer and winter precipitation into Q, E and T result in variations in $\mathrm{SOI}_{\overline{Q}}$, $\mathrm{SOI}_{\overline{E}}$ and $\mathrm{SOI}_{\overline{T}}$. Figures 3a and S7a show a null-hypothesis scenario in which the seasonal partitioning of precipitation matches seasonal water-balance surpluses (P−ET): most winter precipitation becomes streamflow (with relatively little becoming evapotranspired), and most summer precipitation is evapotranspired (with less becoming streamflow). This first scenario would be inferred from the common observation that precipitation often greatly exceeds streamflow in summer but not in winter (Ali et al., 2014), if we assume no inter-seasonal carryover of storage occurs. In that scenario, the $\mathrm{SOI}_{\overline{Q}}$ is below zero, indicating that winter precipitation is over-represented in annual streamflow relative to its proportion of annual precipitation. By contrast, our data (imply that across our Swiss catchments, winter and summer precipitation are present in streamflow in roughly equal proportions relative to their fractions of annual precipitation ($\mathrm{SOI}_{\overline{Q}}\approx 0$). This second scenario, shown in Fig. 3b, suggests that roughly equal proportions of summer and winter precipitation are lost to evapotranspiration ($SOI_{\overline{ET}}\approx 0$). Figure S7b shows that similar SOI patterns could arise if T fluxes are sourced by a consistent volume from each month's precipitation. A third scenario (Fig. 3c) shows the same partitioning of precipitation into Q and ET, but with an additional (hypothesized) partitioning of ET into E and T terms. This result could be consistent with a recent survey of >900 trees around Switzerland (Allen et al., 2019b) which shows that winter precipitation was over-represented in mid-summer tree xylem ($\mathrm{SOI}\approx -0.5$), if we assume that summer precipitation is over-represented in evaporation. This assumption is reasonable, because most terrestrial evaporation consists of interception losses (Wang-Erlandsson et al., 2014), which will be larger in summer (due to greater evaporative demand and leaf area) and must be supplied from current precipitation. However, as explained in the caption to Fig. S7, making the results presented here fully consistent with those of Allen et al. (2019b) would require unrealistically low transpiration rates (Fatichi & Pappas, 2017). Instead, we believe that Allen et al.'s tree-level data somewhat exaggerate the contribution of winter precipitation to transpiration because they only reflect transpiration by forests at the end of a prolonged dry period that likely already depleted subsurface stores of recent precipitation.

Given that evapotranspiration fluxes are typically much larger in summer than in winter, all else equal, $\mathrm{SOI}_{\overline{\mathrm{ET}}}\approx 0$ implies that near-surface storages (e.g., soils or snowpacks) must carry over substantial quantities of winter precipitation that are subsequently evapotranspired in summer. This demonstrates the principle that water fluxes can be out of phase with the inputs that supply them, at a seasonal timescale. A global survey by Jasechko et al. (2016) has shown that most river discharge is more than several months old; our results suggest that substantial fractions of the precipitation that supplies evapotranspiration fluxes may fall several months before that evapotranspiration occurs.

Many aquifers in seasonally warm climates, including Switzerland, carry the isotopic signature of predominantly winter precipitation (Jasechko, 2019; Beria et al., 2018). The over-representation of winter precipitation in aquifer storage does not conflict with our findings that summer and winter precipitation are equally represented in streamflow, if higher-intensity precipitation, which is more common in summer, is more likely to bypass aquifer storage (for example, through shallow subsurface stormflow). This hypothesis is consistent with figures 2a and 2c of Berghuijs et al. (2019), which show that annual maxima of streamflow and daily precipitation rates tend to co-occur in summer in Switzerland (unlike much of the rest of Europe).

Given the widespread availability of streamflow isotope data (Halder et al., 2015) and maps describing precipitation isotope cycles (Allen et al., 2019a; Bowen, 2008), $\mathrm{SOI}_{\overline{\mathrm{Q}}}$ could be calculated for many landscapes and ecosystems. While strong seasonal cycles and high-quality streamflow and precipitation data are required for calculating robust SOI values, such analyses could aid in advancing our basic understanding of how the partitioning of water into ET versus Q depends on its seasonal origin as precipitation. Quantifying the time dependence of this partitioning is crucial in age-based transport models (Botter et al., 2011). Additionally, understanding how the seasonal origins of precipitation relate to it being routed upward versus downward could aid in more accurately using many stable isotope proxies, such as in inferring climate signals from tree-ring δ^{18}O. Longer duration datasets are not only useful for better constraining errors in discharge isotope ratios (which is especially important in regions with smaller seasonal isotope cycles); they may be especially useful for inferring trends in $\mathrm{SOI}_{\overline{\mathrm{Q}}}$ and $\mathrm{SOI}_{\overline{\mathrm{ET}}}$ to better understand how climate change is altering the terrestrial processing of precipitation inputs.

4 Conclusions

Our measurements suggest that the fraction of summer precipitation that becomes streamflow roughly equals the fraction of winter precipitation that becomes streamflow in 12 Swiss catchments. These findings conflict with the hypothetical expectation that smaller fractions of summer precipitation become streamflow because evapotranspiration fluxes are so much larger in summer. Further analyses of streamflow seasonal origins may aid in better understanding how the timing and volume of precipitation shape the routing of water movement through the ecohydrologic cycle.

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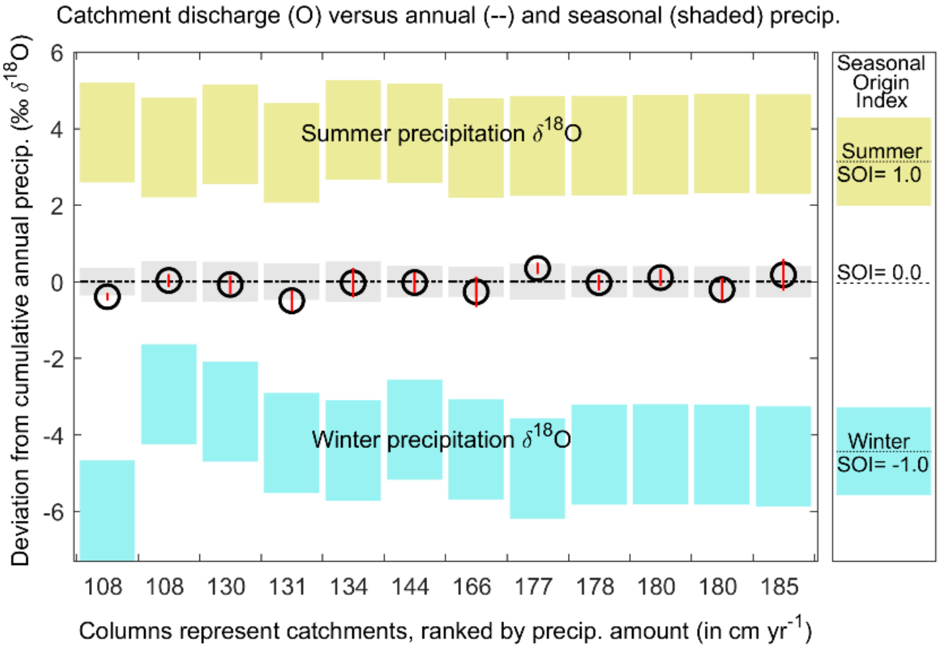

Figure 1. Values of volume-weighted mean streamflow $\delta^{18}O$ (circles), plotted as deviations from catchment-specific volume-weighted mean precipitation $\delta^{18}O$. Catchments are ranked by mean annual precipitation amount (labelled below the horizontal axis). Typical values for mid-summer and mid-winter precipitation $\delta^{18}O$ are shaded in yellow and blue (see section 2.3); the box sizes indicate the variation of monthly values around the fitted sinusoids (see Section 2.3). Red error bars reflect the inter-annual variability in volume-weighted mean streamflow $\delta^{18}O$ values over 4 or 5 years (see Table S1). The gray shading shows the inter-annual variability, across the same years, in volume-weighted-mean annual precipitation $\delta^{18}O$. The panel on the right depicts how isotope values translate to seasonal origin index values.

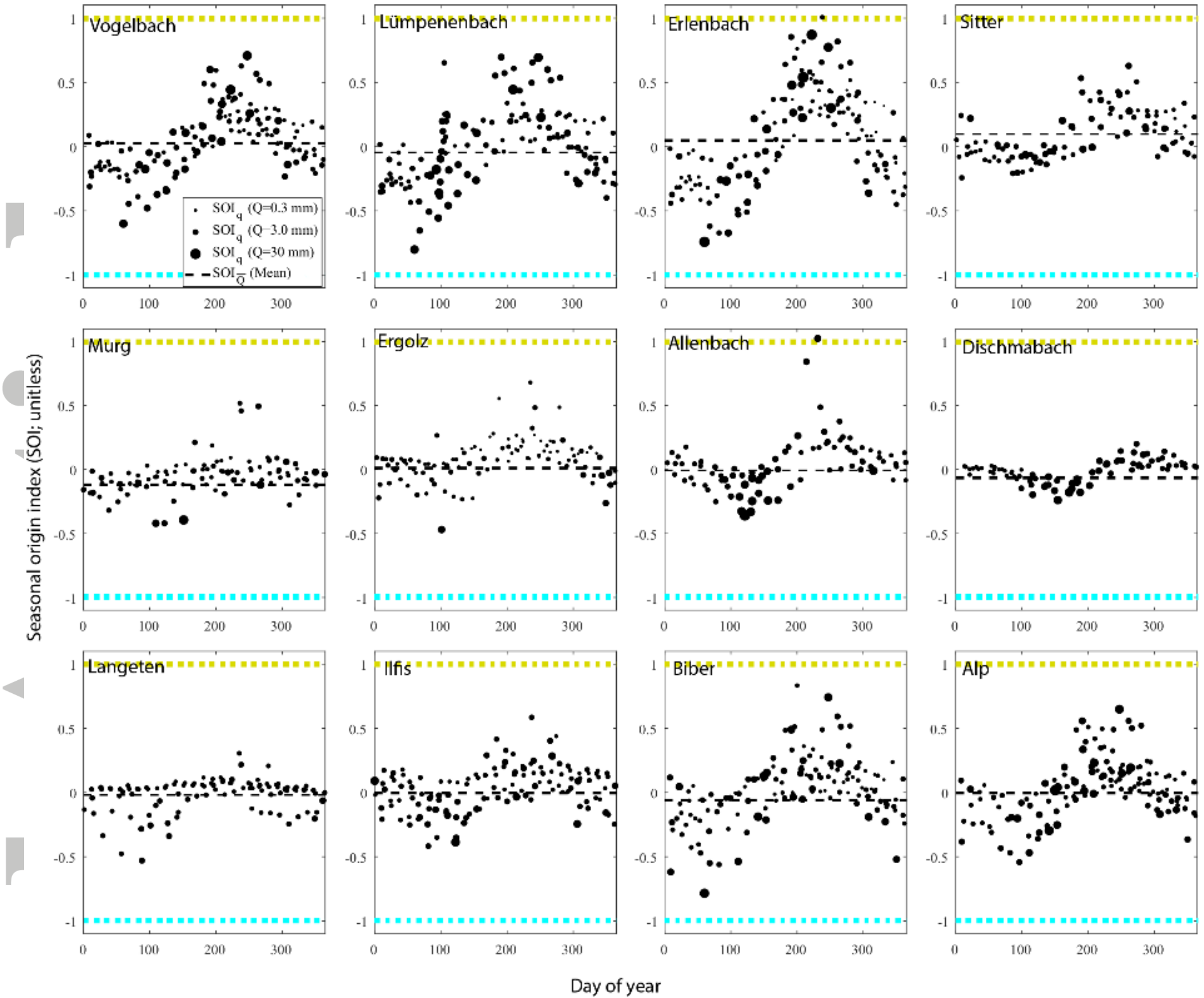

Figure 2 Seasonal origin index values of streamflow samples (SOI$_q$), from all 12 study catchments. Although some catchments are more responsive than others, all had similar SOI$_{\overline{Q}}$ values (marked by the dashed line). These figures also demonstrate the relatively uniform sampling throughout years.

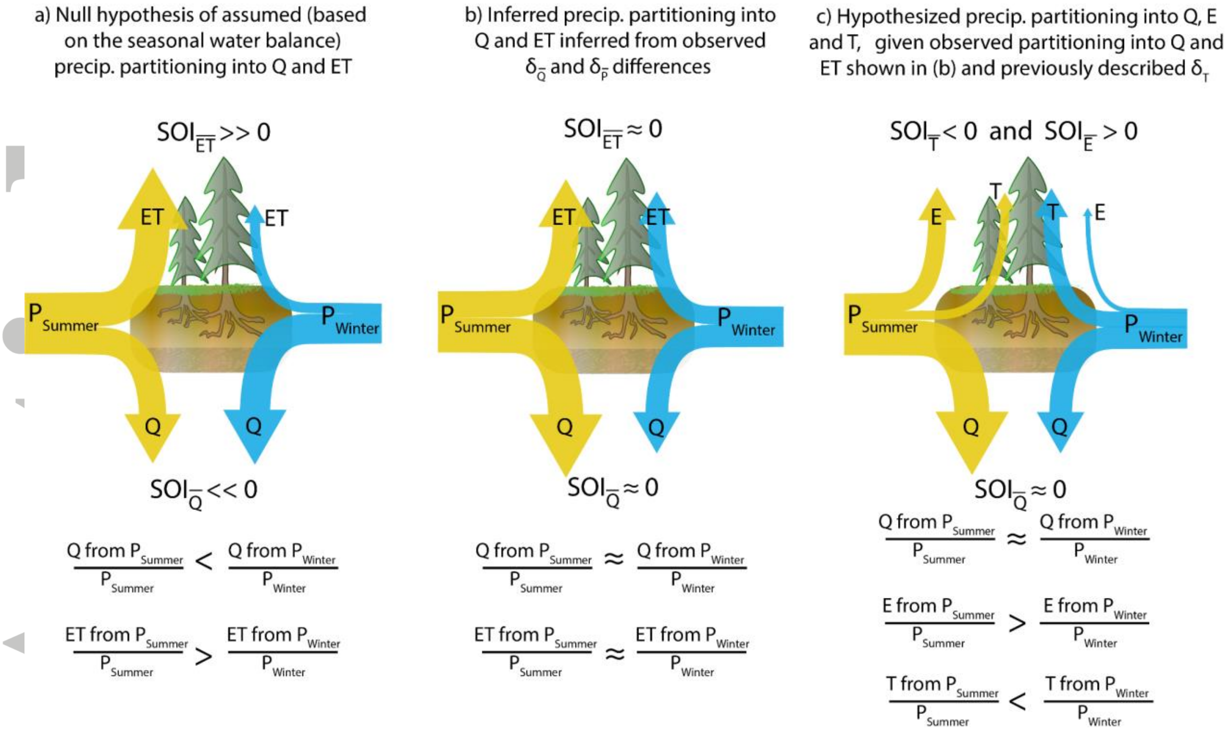

Figure 3 Partitioning of summer and winter precipitation into streamflow and evapotranspiration (given estimated ET efflux magnitudes and seasonal precipitation inputs of the 12 Swiss catchments; see section 2.4). The relative sizes of the arrows reflect the flux magnitudes, but whereas the size of the seasonal precipitation inputs (P_{summer} and P_{winter}) and evapotranspiration and discharge outputs (ET and Q) are based on hydrometrics, the relative partitioning of P_{summer} and P_{winter} into ET or Q is either (a) based on seasonal water balances, (b) based on observed $SOI_{\overline{Q}}$ values, or (c) hypothesized given observed $SOI_{\overline{Q}}$ values. a) The observation that ET fluxes are large in summer and small in winter could lead to the assumption that large fractions of P_{summer} are evapotranspired and most P_{winter} becomes streamflow. b) Our analysis, by contrast, implies that the fraction of P_{summer} that becomes streamflow is roughly equivalent to the fraction of P_{winter} that does so; thus, roughly equal fractions of summer and winter precipitation are lost to evapotranspiration. c) Previous measurements across Swiss forests (Allen et al., 2019b) showed trees largely transpiring P_{winter}; the over-representation of P_{winter} in transpiration (T) is consistent with our findings presented here, if the proportions of P_{summer} lost to evaporation (E) far exceed those of P_{winter} (assuming that the magnitudes E and T are equal).