Responses to referees, list of relevant changes and marked-up manuscript revision

Responses to referee #1

We thank this referee for the fair and useful comments she/he made. We have addressed all comments for improving the clarity and soundness of the paper.

L66. What is the precipitation distribution in year? Would it be possible to show small graph of the annual precipitation and discharge? This would give readers an easy way to get a feeling of the study catchments compared to other catchments.

Response: Because our manuscript is a short technical note that does not focus on a scientific analysis of Can Vila's hydrological properties, in response to this comment we decided to include a sentence on the precipitation and runoff regimes of the Can Vila catchment along with some additional hydro-climatic indices in Table 1. Furthermore, two publications in which Can Vila's climatic and hydrologic properties have been described previously will be cited.

L70. mentions that sampling was done at maximum discharge of 404 mm/day. Caption of Figure 1 mentions that maximum sampled discharge was 226 mm/day.

Response: The maximum recorded discharge was 404 mm/day. However, the maximum discharge that was actually sampled was substantially smaller (226 mm/day). This will be better explained in the revised manuscript to avoid any misunderstanding.

L72. Was sampling done for rising and falling discharges? It would be interesting to see if there is hysteresis in the ywf and the high-frequent sampling might be suitable for this analysis.

Response: At Can Vila, the rate of sampling was higher during the rising limb of the hydrograph than during the falling limb because the discharge increase was much faster during the first. This technical detail will be explained better in the revised text. The possible hysteresis is an interesting question not yet investigated.

Figure 1. If I understand correctly the 'Median discharge' in Figure 1 means the median discharge on the sampling day instead of the discharge at the exact moment of sampling? So all samples are in the figure, while the actual maximum/peak discharge at the moment of sampling on these days was 226 (or 404) mm/day. The authors could consider clarifying this.

Response: Discharges were measured at the time of sampling and were not aggregated but simply transformed into daily flow units for easier comparison with other studies. For our analysis in Fig. 1, we only used those discharge values (in mm/day), during which water samples were collected. Then, the "Median discharge" in Figure 1 is the median value of sampled discharges for each flow regime (e.g., 1st 25%). This will be better explained to avoid this misunderstanding.

L106. Also combining with Eqs 2. Or alternatively the authors could consider writing Eqs. (3) with 'AS(Q)' instead of '(nS + mSQ)', because when combining Eqs. 1, 3 and 5 'As' is not considered a linear function of Q, as in Eqs. 2.

Response: Following the reviewer's suggestion we will include the general expression for c_S Kirchner (2016):

$$c_S(t) = A_S \cdot sin(2\pi f t - \varphi_S) + k_S \qquad \text{Eq. (2rev)}$$

before Eq. (2) in the revised manuscript. Eq. (3) follows from inserting Eq. (2) into Eq. (2rev). In section 3, we will explain better how Eq. (6) was obtained: Eq. (5) was proposed based on the search for an exponential function to describe the data points in Fig. 1. We combined Eq. (5) with Eq. (1), and re-arranged the formula so that only $A_S(Q)$ remains on the left side of the equation:

$$A_S(Q) = A_p \cdot [1 - (1 - F_0) \cdot \exp(-Q(t) \cdot S_d)] \qquad \text{Eq. (6rev)}$$

By inserting Eq. (6rev) into Eq. (2rev), we obtain Eq. (6), which allows for estimating S_d and F_0 from c_S.

L117-164. I compliment the authors on this analysis: it is very interesting to see what happens when highest flows are excluded in sampling and this helps in the comparison with the results of von Freyberg et al 2018. Looking at Figure 3 I wonder if the same results would be found if the lowest flows were excluded, e.g. <0.5 mm/d? It looks like a much better linear fit would then be reached, similar to the fits of von Freyberg et al 2018. Additionally, I am curious if their catchments have higher base flows or that the lowest flows were not sampled.

Response: At Can Vila, excluding the lowest flows does not change the results in Figure 2, unless *DS(logQ)* is used. 0.5 mm/day are exceeded only 32.4% of the time (see red line in Figure (5)), so cannot be considered low flows there. Low flows were also sampled at the Swiss catchments, although they were much higher (see also Figure (5)).

Kirchner, J. W.: Aggregation in environmental systems – Part 1: Seasonal tracer cycles quantify young water fractions, but not mean transit times, in spatially heterogeneous catchments, Hydrol. Earth Syst. Sci., 20, 279–297, https://doi.org/10.5194/hess-20-279-2016, 2016.

Responses to referee #2

We thank the reviewer for the comments and suggestions she/he made. Most of the reviewer's suggestions focus on how the concept of young water fraction and its discharge sensitivity can be applied to analyse the hydrological functioning of the catchments; however, such analyses would go beyond the scope of a technical note. Nevertheless, we will respond to all comments below and make the opportune changes in the manuscript.

(i) When comparing catchments that are characterised by very contrasted climates (as it is the case here), it would be helpful to have more information on the hydrometeorological context. For example, annual precipitation vs annual discharge, a flashiness index (e.g. as per Holko et al., 2011. doi:10.1016/j.jhydrol.2011.05.038) would equally be helpful in this context. A plot showing how stream water samples taken for isotope analysis are distributed along the FDC would also be very informative.

Response: Following this suggestion, several more hydro-climatic indices will be included in Table 1 in the revised manuscript for easier comparison with the catchments studied in von Freyberg et al. (2018) and elsewhere: Annual precipitation and discharge, average precipitation intensity and quick flow index. At Can Vila, where the streamwater sampling frequency increased as a function of discharge, more information on the time exceedance of recorded and sampled discharges will be added. More information about the hydro-climatic properties of the Can Vila catchment is available elsewhere and the relevant publications will be cited.

(ii) In equation 6, the parameters F0 and Sd are obtained via fitting a sinusoid function to the seasonal variation of the isotopic signal in stream water cs(t). In this context, it would be interesting to further investigate and discuss if and how the catchment's wetness state (changing across seasons, but also from one rainfall event to the next) may influence the hydrological functioning of the studied system – and subsequently also the discharge sensitivity of the young water fraction. Soil moisture measurements (if available) or a (daily) water balance calculation could be helpful in this respect.

Response: We agree that these comments would be relevant for analysing the hydrological functioning of the catchment, which is, however, not the scope of our technical note. The technical note is intended to improve a metric primarily designed for describing the time-aggregated response of the catchments.

(iii) Along similar lines, are there any conclusions that can be drawn as to which reservoirs/ compartments actually contribute to streamflow? Did the authors explore to what extent the intensity of precipitation events may influence hydrological responses – and trigger for example similar peak discharge for events that had different initial wetness states. Moderate rainfall may trigger high discharge when the catchment is already close to saturation; likewise, very intense precipitation may trigger similarly high discharge when the catchment has not yet reached saturation. In one case we may have saturation excess overland flow, as opposed to infiltration excess overland flow. How would this influence results and conclusions drawn on the discharge sensitivity of the young water fraction? How much would this also impact any potential catchment intercomparison between catchments with contrasted climate characteristics?

Response: These comments are relevant for extending the application of the young water fraction concept to the analysis of the hydrological functioning of catchments. For our technical note, we utilized the Can Vila data with the intention to demonstrate the limitations of a linear discharge sensitivity of Fyw and to develop an alternative approach. An analysis of the hydrological processes that are responsible for the observed discharge sensitivity in Can Vila would go beyond the scope of the technical note.

(iv) One of the main conclusions of the manuscript is that there is a need for sampling intensively the largest possible range of discharge values along the flow duration curve – with a special focus on (very) high flows. Considering potential hysteretic patterns in the rating curves, how would they impact the sampling protocol and subsequently the conclusions drawn from the obtained data? Is the dataset available for the Can Vila catchment (spanning a wide range of discharge values for O and H stable isotopes in stream water) offering the possibility to investigate this question?

Response: Indeed, the need for high-frequency stream water sampling is an indirect conclusion of our analysis, more widely analysed in Gallart et al. (in review). But this issue is partly offset by the fact that the new exponential S_d metric is much less sensitive to the largest sampled discharges than the original linear *DS(Q)*. At Can Vila, the rate of sampling was higher during the rising limb of the hydrograph than during the falling limb because the discharge increase was much faster than during recession. This opens the possibility to investigate the potential hysteresis in the rating curve, an interesting question not yet attempted.

(v) Possibly, the authors could conclude their work by stating one or two hypotheses that they may consider as being important to be tested in future work (for example in other physiographic contexts).

Following this comment we will include some open questions directly related to the role of the sampling design in robustly determining S_d and F_{yw}, as well as whether S_d, F_0 and F_{yw} are correlated with each other when diverse catchments are compared.

Gallart, F., Valiente, M., Llorens, P., Cayuela, C., Sprenger, M., Latron,J.: Investigating young water fractions in different hydrological compartments of a small Mediterranean mountain catchment: both precipitation forcing and sampling frequency matter. *Hydrol. Process*. (in revision).

Relevant changes made in the manuscript

Many small changes have been made following referees' comments. The more relevant changes are i) more data shown in table 1 and ii) the inclusion of more general questions at the end of the comparison between different catchments and the conclusion, as suggested by the referees

Technical note: An improved discharge sensitivity metric for young water fractions.

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Abstract: Recent virtual and experimental investigations have shown that the young water fraction F_{yw} (i.e. the proportion of catchment outflow younger than *circa* 2-3 months) increases with discharge in most catchments. The discharge sensitivity of F_{yw} has been defined as the rate of increase in F_{yw} with increasing discharge (Q), and has been estimated by the linear regression slope between F_{yw} and Q, hereafter called $DS(Q)$. The combined use of both metrics, F_{yw} and $DS(Q)$, provides a promising method for catchment inter-comparison studies that seek to understand streamflow generation processes. Here we explore the discharge sensitivity of F_{yw} in the intensively sampled small Mediterranean research catchment Can Vila. Intensive sampling of high flows at Can Vila allows young water fractions to be estimated for the far upper tail of the flow frequency distribution. These young water fractions converge toward 1 at the highest flows, illustrating a conceptual limitation in the linear regression method for estimating $DS(Q)$ as a metric of discharge sensitivity: F_{yw} cannot grow with discharge indefinitely, since the fraction of young water in discharge can never be larger than 1. Here we propose to quantify discharge sensitivity by the parameter of an exponential-type equation ~~expressing~~ that expresses how F_{yw} varies with discharge. The exponential parameter (S_d) approximates $DS(Q)$ at moderate discharges where F_{yw} is well below 1; however, the exponential equation and its discharge sensitivity metric better capture the non-linear relationship between F_{yw} and Q and are robust with respect to changes in the range of sampled discharges, allowing comparisons between catchments with strongly contrasting flow regimes.

1 Recalling the definition of the discharge sensitivity of the young water fraction

The seasonal cycles of stable isotopes in precipitation are damped and phase-shifted as they are transmitted through catchments, and thus can be used to infer properties of catchment travel-time distributions (e.g. DeWalle et al., 1997; McGuire and McDonnell, 2006). The young water fraction (F_{yw}), or the proportion of catchment outflow younger than *circa* 2-3 months, can be estimated as the ratio between the seasonal cycle amplitudes of stable water isotopes in precipitation and stream water. This ratio consistently predicts F_{yw} across a wide range of transit time distributions, whereas the same range of distributions yields widely varying mean transit times (Kirchner, 2016a).

The young water fraction usually increases with stream discharge (Kirchner, 2016b). To account for this flow-dependency in their study of 22 Swiss catchments, von Freyberg *et al.* (2018) distinguished between time-weighted (F_{yw}) and flow-weighted (F^*_{yw}) young water fractions and introduced the 'discharge sensitivity of the young water fraction' (which we term $DS(Q)$) as a metric of the progressive increase of F_{yw} with increasing catchment discharge (Q). Thus, by combining the mean F^*_{yw} and its sensitivity to discharge, catchment young water response can be classified in two dimensions: catchments with low or high F^*_{yw} and with low or high $DS(Q)$ (FigureFig. 10 in von Freyberg *et al.*, 2018). Because these two variables did not correlate with each other and correlated with different catchment characteristics, von Freyberg *et al.* (2018) suggested that F^*_{yw} and $DS(Q)$ are two independent metrics that can be informative in catchment inter-comparison studies.

These authors used the linear slope between F_{yw} (-) and discharge rate Q (mm d^{-1}) for calculating $DS(Q)$ (d mm^{-1}). The use of discharge rate instead of volume rate (m^3 d^{-1}) is sensible, because of its independence from catchment area. Von Freyberg *et al.* (2018) They justified the choice of using Q as forcing variable instead of log(Q), which is more sensitive to low flows, by the main focus of the study being storm runoff generation.

Von Freyberg *et al*. (2018) determined *DS(Q)* through a non-linear fitting algorithm. These authorsThey aAssumeding that the seasonal cycle amplitude– (A_S) of the stable water isotopes signal in stream water (A_S) varies with Q, but the corresponding cycle amplitude in precipitation (A_P) does not, then such that F_{yw} varies with Q as:

$$F_{yw}(Q) = A_S(Q)/A_P \qquad (1)$$

and the isotopic signal of stream water $c_S(t)$ (‰) follows a sinusoid function

$$c_S(t) = A_S \cdot sin(2\pi f t - \varphi_S) + k_S \qquad (2)$$

where φ_S is the phase of the seasonal cycle (rad), t is the time (fractional decimal years), f is the frequency (years^{-1}, equal to 1 for a full annual cycle) and k_S (‰) is a constant describing the vertical offset of the isotope signal.

Then Iif A_S is approximated as a linear function of Q,

$$A_S(Q) = n_S + m_S Q \qquad (32)$$

Eq. (2) can be rewritten astThe slope (m_S) and the intercept (n_S) of this linear function can be obtained with the equation resulting from itsby insertion into the fitting a sinusoid function Eq. (2)to the seasonal variation of the isotopic signal of stream water $c_S(t)$ (‰):

$$c_S(Q,t) = (n_S + m_S Q) \cdot sin(2\pi f t - \varphi_S) + k_S \qquad (43)$$

and the slope (m_S) and the intercept (n_S) of Eq. (3) can be obtained from time series of c_S and Q by fitting the four parameters m_S, n_S, φ_S, and k_S in Eq. (4) using non-linear fitting methods.

~~where φ_S is the phase of the seasonal cycle (rad), t is the time (decimal years), f is the frequency (years^{-1}, equal to 1 for a full annual cycle) and k_S (‰) is a constant describing the vertical offset of the isotope signal.~~

Combining Eqs. (1) and (3~~2~~) yields:

$$F_{yw}(Q) = \frac{n_S}{A_P} + \frac{m_S}{A_P} Q \qquad (5~~4~~)$$

Thus $DS(Q)$, the linear slope of the dependence of F_{yw} on Q, can be approximated as m_S/A_P, which has units of Q^{-1}.

2 Investigating discharge sensitivity of the young water fraction in a small Mediterranean catchment

We applied the approach outlined above to the small Mediterranean Can Vila catchment (Vallcebre Research Catchments, Llorens *et al.*, 2018). The objectives were to better understand the Can Vila catchment's hydrology and to test the F_{yw} and discharge sensitivity concepts ~~and methods~~ in an environment that was different, in terms of climate, catchment characteristics and sampling strategy, from the Swiss catchments studied by von Freyberg *et al.* (2018). This technical note focuses only on the aspects of this research that are relevant to the estimation of F_{yw} and its discharge sensitivity, as other aspects of the Can Vila catchment study will be presented in a separate publication (Gallart *et al.*, in review~~preparation~~).

The Can Vila catchment (Table 1) is a 0.56 km^2, semi-humid ~~(mean annual precipitation = 880 mm)~~ Mediterranean mid-elevation~~altitude~~ (1,115-1,458 m a.s.l) catchment with a rainfall-dominated flow regime. Stream discharge ~~is highly varying~~varies greatly, from zero flows during some summer periods to ~~few days lasting~~several-day-long floods associated with saturation generation mechanisms during wet periods (Latron and Gallart, 2008; Latron *et al.*, 2009). In addition to long-term hydrometric monitoring since the early 1990's, precipitation and stream water stable isotopes were sampled from May 2011 to September 2013 and from May 2015 to May 2016. During the isotope sampling period, 5-minute discharges ranged from zero to 2.621 m^3 s^{-1} (equivalent to 4.68 m^3 s^{-1} km^{-2} or 404 mm d^{-1}), with a highly skewed flow duration curve (i.e., 30 % of total stream discharge flowed through the gauging station during 1 % of the time). A 'smart sampling strategy' was used to obtain flow-representative water samples, consisting of the combination of two automatic water samplers, one triggered by time and the other by flow. The sampling frequency was higher during the rising limb of the hydrograph ~~was higher~~ than during the falling limb, in order to compensate for ~~its~~the rising limb's shorter duration~~-~~. The resulting sampling intervals varied between 30 minutes and 26 days with a maximum sampled discharge equivalent to 226 mm d^{-1}. We investigated the young water fraction and its discharge sensitivity for the Can Vila catchment ~~by~~ using this ~~40~~ 40-month-long isotope time series containing 464 precipitation and 858 streamflow samples. Given the drier climate, the smaller catchment area and the much finer time scale for sampling, this data set extends the range of catchments investigated by von Freyberg *et al.* (2018).

For the Can Vila catchment, the flow-weighted young water fraction (F^*_{yw}=0.226±0.028) was much larger than the time-weighted young water fraction (F_{yw}=0.061±0.008). Both values fell within the range of those reported by von Freyberg *et al.* (2018), but the ratio between them was larger than at the Swiss catchments, suggesting that young water fractions are more sensitive to discharge at Can Vila than at most of the Swiss sites.

To further explore the discharge sensitivity *DS(Q)* at Can Vila, we estimated young water fractions for different quantiles of the flow regime (similar to ~~Figure~~Fig. 7 in von Freyberg *et al*., 2018), extending the range to portray the highest flows (up to the top 0.25 ~~%, ~~%; ~~(Figure~~Fig. 1). Our flow-dependent sampling strategy intensively sampled these high flows, which conventional sampling at regular time intervals would miss. Figure 1 shows that F_{yw} increases with increasing discharge, from nearly 0 at the lowest discharge to nearly 1 for Q≥24 mm d^{-1}. This behaviour partly corresponds to a high-*DS(Q)* type 2 catchment in ~~Figure~~Fig. 10 in von Freyberg *et al.* (2018). However, the non-linear behaviour of F_{yw} with increasing flow shown in ~~Figure~~Fig. 1 is inconsistent with a linear model of discharge sensitivity. Very small F_{yw} values (<0.1) during baseflow are consistent with the long (7.7 years) mean transit time of base flows obtained in this catchment (Gallart *et al.,* 2016), whereas the high sensitivity of F_{yw} to discharge reflects the varying pre-event water contributions (30-90 %) observed for different flow events (Llorens *et al*., 2018).

Equations (4~~3~~) and (5~~4~~) (numbered 9 and 10 in von Freyberg *et al*., 2018) yield a discharge sensitivity *DS*(*Q*) value of 0.0128~~098~~±0.0017~~2~~ d mm^{-1} for the Can Vila catchment (grey line in ~~Figure~~Fig. 1), which is among the smallest discharge sensitivities obtained for the 22 Swiss catchments, in contrast with the visibly high discharge sensitivity of Can Vila over the range of its flow regime. ~~Figure~~Fig. 1 shows that the linear design of *DS*(*Q*) is clearly inadequate to capture the asymptotic convergence of the young water fraction toward F_{yw}≈1 at the far upper tail of the flow distribution. Highly dynamic catchments such as Can Vila, and flow sampling strategies like those employed here, demonstrate that a non-linear discharge sensitivity function is needed.

3 Defining alternative metrics for discharge sensitivity of the young water fraction

An alternative, non-linear model can be derived by noting that the sum of old and young water fractions is always 1, and by assuming that the old water fraction decreases with increasing discharge and asymptotically approaches 0 (and thus the young water fraction asymptotically approaches 1) as Q approaches infinity. We propose the following equation, where the old water fraction decreases exponentially with increasing Q, and the young water fraction grows accordingly:

$$F_{yw}(Q) = 1 - (1 - F_0) \cdot \exp(-Q \cdot S_d) \qquad (6~~5~~)$$

where F_0 (-) is the virtual F_{yw} for ~~virtual~~ Q=0 and S_d (unit of Q^{-1}) is the new discharge sensitivity metric. The red curve in ~~Figure~~Fig. 1 shows the application of this equation to the Can Vila data.

On combining Eqs. (1)~~, (3)~~ with~~and~~ (6~~5~~)~~,~~ and re-arranging the formula so that only $A_S(Q)$ remains on the left side of the equation, we obtain:

$$A_s(Q) = A_P \cdot [1 - (1 - F_0) \cdot \exp(-Q \cdot S_d)] \qquad (7)$$

Finally, by inserting Eq. (7) into Eq. (4), the F_0 and S_d parameters can be obtained by fitting a sinusoid function to the seasonal variation of the isotopic signal of stream water $c_S(t)$:

$$c_S(Q,t) = A_P \cdot [1 - (1 - F_0) \cdot \exp(-Q \cdot S_d)] \cdot sin(2\pi f t - \varphi_S) + k_S \qquad (8~~6~~)$$

We obtained the F_0 and S_d parameters with a non-linear analytic Gauss-Newton algorithm in which we used streamflow rates as weights.

Taking the derivative of Eq. (6~~5~~) with respect to Q directly yields the result that the local discharge sensitivity $\frac{dF_{yw}(Q)}{dQ}$ at low discharges will be directly related to (and in many cases nearly equal to) S_d:

$$\begin{aligned}\frac{dF_{yw}(Q)}{dQ} &= (1 - F_0) \cdot S_d \cdot \exp(-Q \cdot S_d) \\ &\approx (1 - F_0) \cdot S_d \text{ for } Q \ll S_d^{-1} \\ &\approx S_d \text{ for } Q \ll S_d^{-1} \text{ and } F_0 \ll 1\end{aligned} \qquad (9~~7~~)$$

When ~~Because~~ F_0 is~~will typically be~~ small, S_d will ~~typically~~ be a good approximation to the slope of the relationship between F_{yw} and Q at discharges that are low enough to keep F_{yw} still far from 1.

4 Sensitivity of the discharge sensitivity metrics to changes in data availability at the Can Vila catchment

We used the Can Vila dataset to test the robustness of the S_d metric, in comparison with the original *DS*(*Q*) metric defined by von Freyberg *et al.* (2018) and with several alternative metrics designed to reduce or avoid some of the *DS*(*Q*) metric's limitations. We investigated how these metrics changed when we excluded the discharge and water samples for ~~determining F_{yw} that corresponded to~~ the highest flows ~~were excluded~~ from the Can Vila dataset (~~Figure~~Fig. 2). This allowed us to test how these discharge sensitivity metrics were affected by the availability (or, conversely, the lack) of tracer data encompassing extreme flows.

For this purpose, we compare the new S_d metric, the original *DS(Q)* metric and several dimensionless options that used log(Q), Q/Q_{max}, and Q/Q_{mean} instead of Q in the calculations (Q_{max} and Q_{mean} correspond to the maximum and mean values of the discharge rates $Q(t)$ associated with stream water sampling). We call the resulting discharge sensitivity metrics

DS(logQ), *DS(Qmax)* and *DS(Qmean)*, respectively. Note that *DS(Qmax)* and *DS(Qmean)* may be obtained by multiplying any previously calculated *DS(Q)* value by Q_{max} or Q_{mean}.

The new exponential S_d metric values (~~Figure~~Fig. 2a) show some scatter but are robust to changes in the underlying data, exhibiting no systematic trend as the ~~high~~ high-flow observations were progressively discarded. In contrast, *DS(Q)* is highly sensitive to changes in the analysed range of discharges (~~Figure~~Fig. 2b), rapidly increasing (by a factor of 5) on exclusion of the highest flows from the calculations and reaching its maximum value on exclusion of the upper 5 % of flows (Q>4.82 mm d^{-1}), corresponding to everything above the green dot (Top 5%) in ~~Figure~~Fig. 1. Note that, as suggested by Eq. (9~~7~~), *DS(Q)* takes values similar to S_d when the highest flows are excluded. *DS(logQ)* declines promptly on omission of the highest flows (~~Figure~~Fig. 2c), but remains stable afterwards. *DS(Qmean)* behaves similarly to *DS(Q)*, i.e. it is smallest when the complete data set is used and is largest on exclusion of the highest 5 % of flows from the analysis (~~Figure~~Fig. 2d). Finally, ~~Figure~~Fig. 2e shows that *DS(Qmax)* becomes largest with the complete data set and sharply decreases to much smaller values on exclusion of the highest 1 % of flows from the calculations, but undergoes just a little progressive decrease when more data of the flow distribution are excluded.

In summary, S_d is clearly more robust than the other discharge sensitivity metrics to changes in the sampled range of flows. It also has the distinct advantage that Eqs. (7~~5~~)-(8~~6~~), unlike Eqs. (3)-(4), can never yield F_{yw} values larger than 1. One can see from Eqs. (6~~5~~)-(8~~7~~) that S_d functions as both a shape parameter, controlling how non-linear F_{yw} is as it approaches 1, and a scale parameter, controlling the slope of the relationship between F_{yw} and Q at low or moderate discharges.

5 Comparing discharge sensitivities at Can Vila and the Swiss catchments.

Figure 3 compares the quantile plot of ~~Figure~~Fig. 1 for the Can Vila catchment and the quantile plots of ~~Figure~~Fig. 7 in von Freyberg *et al*. (2018) for the Swiss catchments of Langeten, Biber and Ilfis, which exhibit very different young water fractions and/or discharge sensitivities (Table 1). The F_0 and S_d metrics were calculated from Eq. (8~~6~~) and good fits were obtained between the individual F_{yw} values and the median discharges as shown by the red curves. For comparison, grey curves correspond to the linear approach using E~~e~~q. (5~~4~~).

We find that young water fractions in the Can Vila catchment ~~are among the most sensitive to discharge~~have a discharge sensitivity (~~largest~~ S_d) similar to that of the ~~between the~~ Langeten and the Biber catchments. By contrast, t~~T~~he young water fractions of the Ilfis catchment have almost no discharge sensitivity. Although Can Vila has a low ~~Despite having the lowest~~ F_0 value, which is in line with its baseflow being several years old, its ~~the~~ large discharge sensitivity ~~value observed at Can Vila~~ expresses well the highly dynamic streamflow regime in this Mediterranean mountain environment.

~~While~~ Although the linear expression of discharge sensitivity (*DS(Q),* Eq. 5~~4~~) provides a reasonable fit for the low-to-medium flow regimes of the Swiss sites, it fails to capture the highly non-linear dependence of F_{yw} on Q at Can Vila, evidenced by the high flows sampled there (~~Figure~~Fig. 3a). In addition, ~~Figure~~Fig. 3 shows a major drawback of the linear approach, namely that it ~~which~~ predicts F_{yw} values larger than 1 for high-flow conditions.

The four catchments compared here differ considerably in catchment area and median discharge (Table 1), which often challenges a robust inter-comparison analysis. However, ~~we show~~Fig. 3 shows that Eq. (6) efficiently estimates the sensitivities (S_d) of F_{yw} on Q across these catchments.

The comparison of the S_d and *DS(Q)* metrics for Can Vila and the 22 Swiss catchments studied by von Freyberg *et al.* (2018) demonstrates that the *DS(Q)* linear approach approximates small discharge sensitivities reasonably well (~~Figure~~Fig. 4). However, for relatively high discharge sensitivities, the linear model tends to predict smaller and more variable *DS*(Q) values. This behaviour may be attributed to the fact that, as shown in ~~Figure~~Fig. 2b, when S_d is high, the value of *DS(Q)* decreases if there are ~~high~~ high-flow samples that reduce the linear slope between F_{yw} and Q (as ~~it happens~~occurs in ~~Figure~~Fig. 1).

In order to compare the frequencies of occurrence of Q and F_{yw} in the diverse catchments, the same points shown in Figure 3 are ploted on a single log-probabilistic graph in ~~Figure~~ Fig. 5. It presents the information as flow duration curves, using the corresponding quantile frequencies, the log-normal distributions fitted to the flow quantiles and the $F_{yw}(Q)$ lines obtained by applying Eq. (6~~5~~) to the discharges. Figure 5 shows differences in behaviour between Can Vila and the three Swiss catchments due to the combination of flow distribution and discharge sensitivity of F_{yw} that are only vaguely visible in Figure 3. This graph also allows anticipation of the F_{yw} values that might be obtained if more samples would be collected during high flows (low exceedance frequencies) in the study catchments.

The question arises where (in what kinds of catchments and in what types of climates) F_{yw} becomes high enough at high flows that it approaches unity, and thus an exponential model is needed to describe F_{yw} at high flows. This is a question that depends not only on catchment behaviour but also on the sampling design and the range of investigated discharges. For example, the results shown ~~above~~in Fig. 3 for the Biber catchment demonstrate that, if the linear sensitivity ~~is~~were applied, a value of ~~*DS(Q)*~~F_{yw}=1 would be reached for a discharge of 26.8 mm d^{-1}. This discharge is exceeded 0.38% of the time, i.e., 1.4 days per year, at the Biber catchment (see the solid green line in Fig. 5). ~~; after the log-normal fit of the flow distribution curve shown in Figure 5, this discharge would be exceeded by 0.38% of time, i.e., 1.4 days per year.~~ Furthermore, the linear character of DS(Q) makes it sensitive to the sampled discharges (Fig~~ure~~. 2b) so it may be more vulnerable to insufficient sampling designs and likely to show inconsistent behaviour in sensitive catchments (Fig~~ure~~. 4).

Conclusions

The discharge sensitivity of the young water fraction is a promising metric for investigating streamflow generation processes and for catchment inter-comparison studies. However, the original discharge sensitivity approach, based on fitting a linear ~~regression~~ slope ~~approach~~ between the young water fraction (F_{yw}) and discharge (Q), turns out to be inadequate when applied to ~~an~~ the intensively sampled ~~small~~ Can Vila catchment; ~~, because~~ it ~~fails to~~does not accurately predict F_{yw} during high flows, which consist almost entirely of young water. ~~The~~ Can Vila's young water fractions converge toward 1 at the highest flows, revealing a conceptual limitation in the linear ~~regression~~ approach, which can predict impossible values of ~~because~~ F_{yw} >1~~can never be larger than 1~~. ~~Yet, as~~Because F_{yw} is ~~defined to range~~confined between 0 and 1, whereas Q may vary by several orders of magnitude, ~~the~~ linear ~~regression approach for estimating~~estimates of discharge sensitivity ~~is sensitive to~~will vary, depending on the highest Q values at which F_{yw} estimates are available; this~~,~~ potentially hampers robust comparisons of discharge sensitivities ~~at~~ between catchments with very different flow regimes and sampling designs.

We propose an alternative, exponential-type approach for estimating discharge sensitivity (Eq. 6~~5~~), to overcome the limitations of the linear approach. The parameters of this exponential equation are F_0 ~~(-)~~, i.e., virtual F_{yw} for ~~virtual~~ zero discharge, and S_d ~~–, (Q^{-1}) that~~which represents the shape of the curve for the increase of F_{yw} with increasing Q. The exponential ~~regression-based~~ S_d metric outperforms the linear ~~regression-based~~ discharge sensitivity metric in terms of physical soundness and lower sensitivity to changes in available tracer and discharge information.

As the proposed S_d metric has dimensions inverse to discharge Q, its value depends on the units of Q used in Eqs. (6~~5~~) and (8~~6~~). Nevertheless, the S_d metric exhibited consistent behaviour across wide ranges of discharges sampled in the same catchment and between catchments of diverse sizes and flow regimes.

We hypothesize that, if estimated from tracer samples ~~obtained with sampling rates~~that adequately capture ~~adequate to~~ the runoff dynamics, the ~~joint use~~three metrics of F_{yw}, F_0 and S_d ~~metrics~~ will help ~~to compare~~in comparing ~~the~~ runoff generation behavior in ~~response of~~ catchments with ~~a wide range of~~widely varying characteristics. The F_{yw} ~~first~~ metric, though being sensitive to ~~the~~ catchment wetness, provides an overall measure of the young water contribution; the F_0~~second c~~ metric characterizes base flows and the S_d metric quantifies ~~third how important is~~ how much F_{yw} changes as ~~the activation of rapid water transmission paths when~~ catchment wetness increases.

Data availability. The Swiss isotope data are available as detailed in von Freyberg *et al*. (2018). The Can Vila isotope data are available from Jérôme Latron upon request.

Author contributions. JL and PL designed the isotope sampling strategy at Can Vila and provided measurements. FG and MV analyzed the Can Vila data set. FG, JK and JF developed the new approach. FG prepared the paper with contributions from JF, JK, JL and PL.

Competing interests. The authors declare that they have no conflict of interest.

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Table

Table 1: Main characteristics and metrics of the catchments shown in Fig~~ures~~s. 2 and 3. *P* is precipitation, *Q* is the stream discharge, F^*_{yw} is the flow-weighted young water fraction, F_0 is the virtual young water fraction for ~~virtual~~ zero flow, and S_d is the proposed discharge sensitivity metric of the young water fraction. ~~,~~ F_0 and S_d ~~the last two~~ are defined in Eq. (6~~5~~).

Catchment	Area (km²)	Mean *P* (mm·year⁻¹)	Mean *P* Intensity (mm d⁻¹)	M~~m~~edian *Q* (mm·d⁻¹)	C~~c~~oefficient of variation *Q* (%)	Quick-flow Index (-)	F^*_{yw} (-)	F_0 (-)	S_d (d·mm⁻¹)
Can Vila	0.56	880	8.6	0.212	304~~451.5~~	0.42	0.23	0.020±0.030	0.062±0.011
Langeten	60.3	1,297	4.7	1.49	62~~1.7~~	0.30	0.07	-0.043±0.034	0.070±0.017
Biber	31.6	1,685	5.8	1.54	149~~.4~~	0.72	0.39	0.170±0.059	0.058±0.013
Ilfis	187.9	1,443	5.2	1.74	114~~3.6~~	0.53	0.12	0.110±0.025	0.003±0.005

Figures

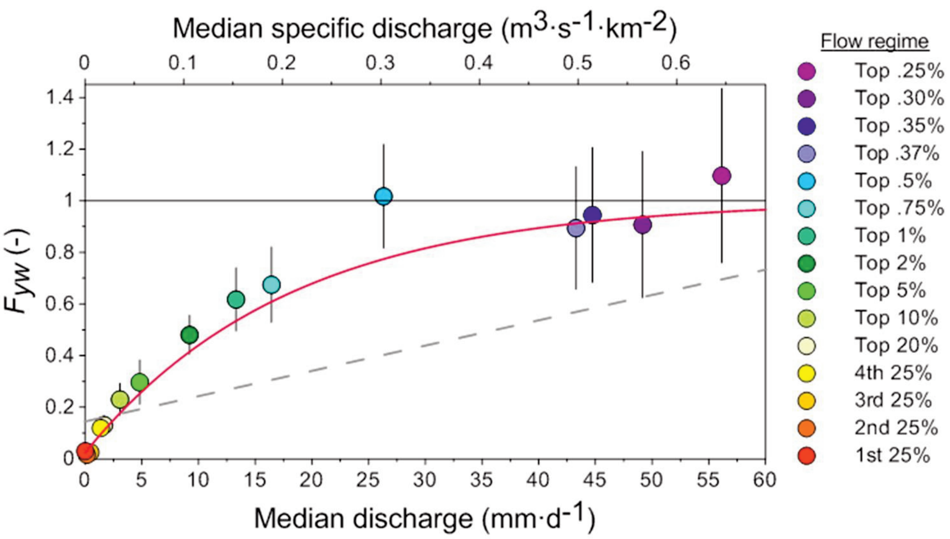

Figure 1: Variation in time-weighted young water fraction at the Can Vila catchment with increasing quantiles of the flow duration curve. The dashed grey line represents Eq. (5~~4~~) and the red curve represents Eq. (6~~5~~), using parameters obtained by fitting Eqs. (3) and (6), respectively, to all the stream water $\delta^{18}O$ isotope values. Discharge values are instantaneous measurements expressed in daily units. Maximum sampled discharge was 226 mm d⁻¹. Vertical bars represent standard errors.

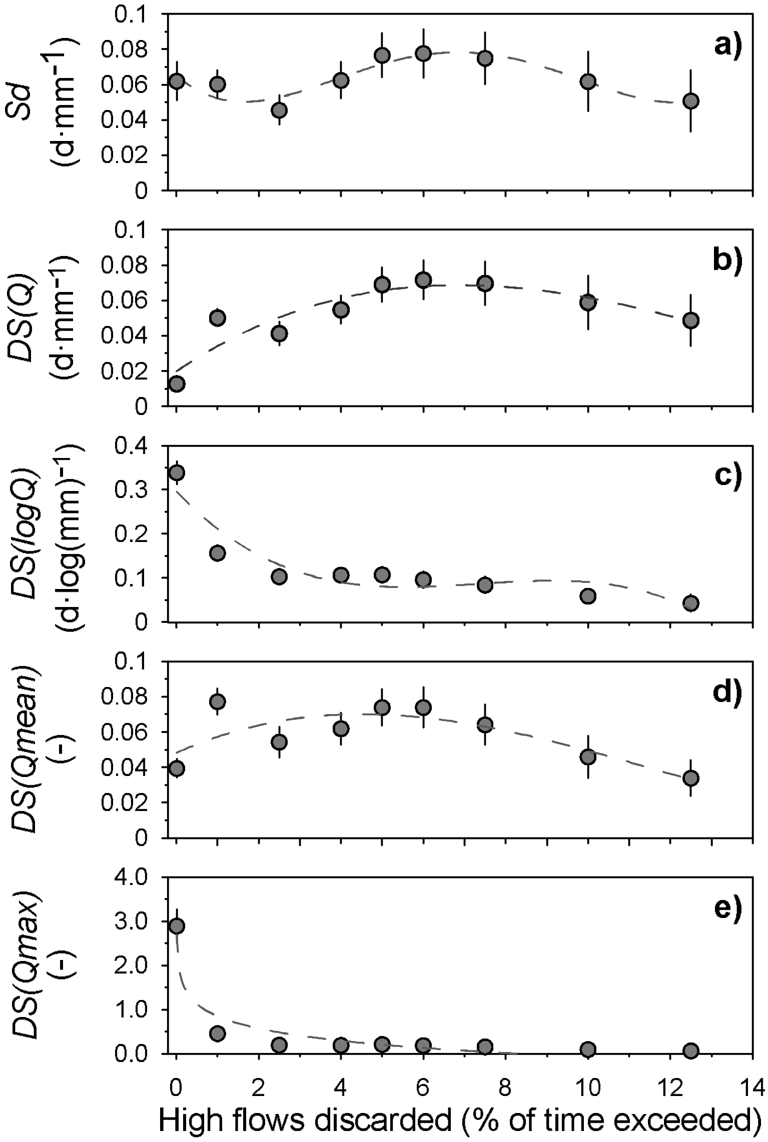

Figure 2: Behaviour of the different discharge sensitivity metrics in the Can Vila catchment when measurements corresponding to the highest flows are sequentially discarded. Percentage of time exceeded refers to the flow duration curve. Vertical bars represent standard errors and dashed lines are ancillary polynomial fits.

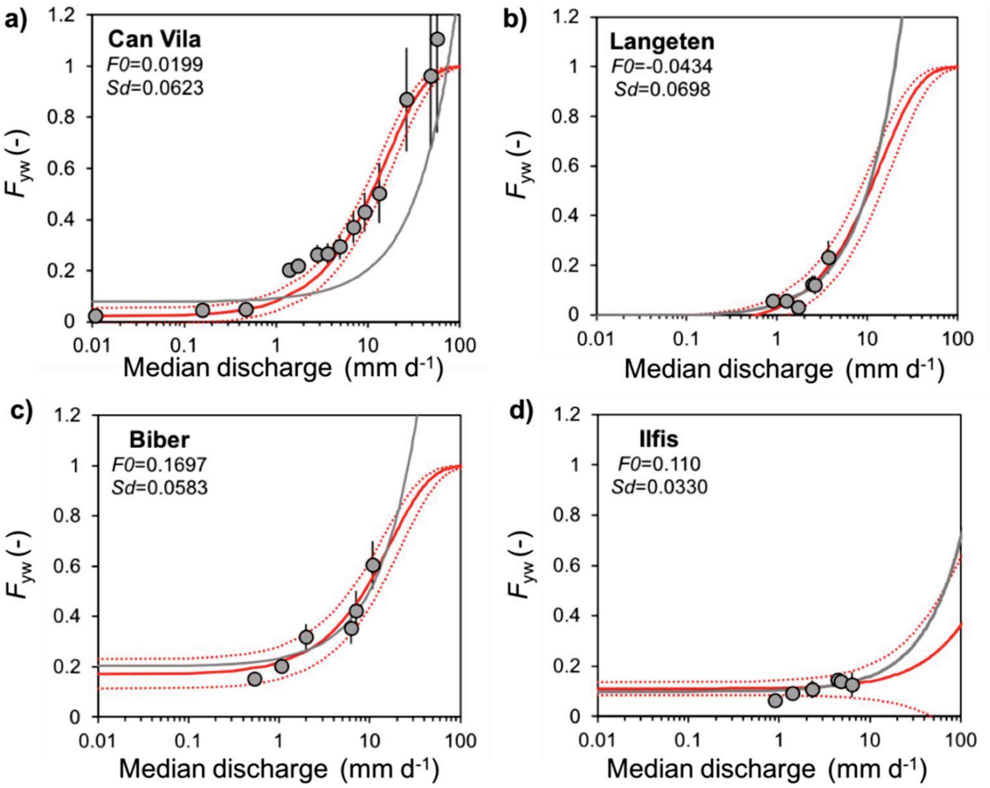

Figure 3: Sensitivity of the young water fraction on discharge for the a) Can Vila, b) Langeten, c) Biber and d) Ilfis catchments. The red curves represent exponential fits (Eq. 65), with parameters S_d and F_0 obtained through volume-weighted non-linear fitting of Eq. (86) to the stream water isotope data; red dashed lines indicate ±1 standard error. The grey curves represent the linear fit (Eq. 54).

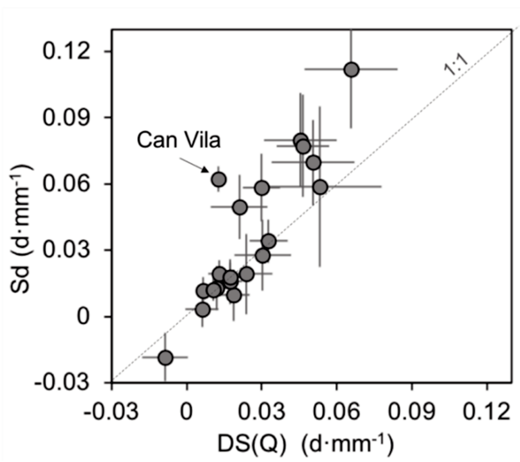

Figure 4: Comparison of discharge sensitivities *DS(Q)* and S_d for 20 Swiss catchments and Can Vila (excluding Aach and Mentue for which unrealistic values for *DS(Q)* or S_d were obtained). Error bars indicate ±1 standard error.

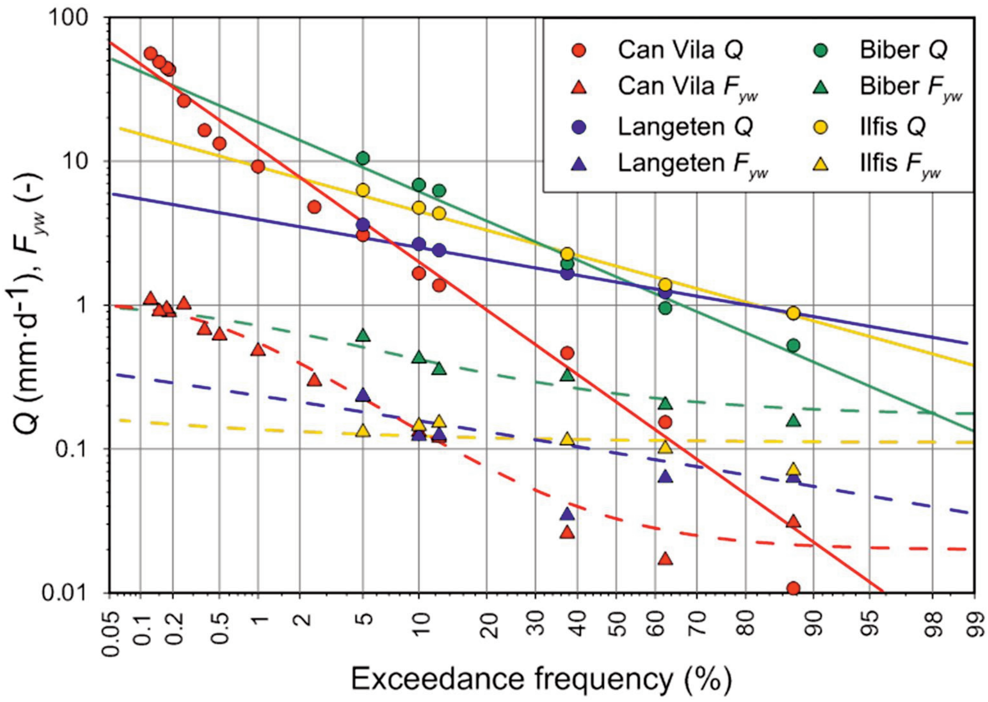

Figure 5: Discharges and young water fractions from Figure 3 plotted against the respective quantile frequencies, along with the log-normal distributions fitted to discharges (continuous solid lines) and distributions of young water fractions (dashed curves) obtained by applying Eq. (65).