

Rebuttal of the paper “Stream flow recession patterns can help unravel the role of climate and humans in landscape co-evolution” by Bogaart, van der Velde, Lyon and Dekker

Editorial review

The paper received two reviews that are very helpful in guiding the authors in the necessary revisions. One reviewer was particularly critical assessing the scientific quality only as fair. I appreciate the work of the researchers and can well see that this paper gets published in HESS, however, revisions are necessary. I would like to invite the authors to submit a revised version (indicating the changes with using track-changes) and a rebuttal.

We thank the editor, two referees, four peers and three students for their careful reading of our paper. We will address the referee and peer comments in chronological order, followed by the three student reviews.

Short comment #1a (SC C3901; David Rupp and Ross Woods)

The authors suggest characterizing recession dynamics for a catchment by defining “the timescale for which half of the initial reservoir storage is depleted.” This is a rational approach for a nonlinear reservoir, but has the disadvantage that since every recession has a different implied initial reservoir storage, every recession also has a different timescale. This does reflect reality, but does not provide a single timescale for each catchment.

The authors then equate a characteristic timescale of recession T to a function of the power-law recession parameters “ a ”, “ b ”, and a “characteristic discharge at the start of the recession” Q_0 (Eq. 5). They claim that because T is proportional to $1/a$, $1/a$ indicates a recession time scale.

*However, they ignore that the units of “ a ” in Eq. 5 are a function of “ b ”; “ a ” has units $L^{3(1-b)} * T^{(b-2)}$, or, if discharge Q is divided by catchment area A , it has units of $L^{(1-b)} * T^{(b-2)}$. “ a ” is therefore not a recession time scale except for the case of “ b ” = 1.*

(Note: we did not find where the authors state that Q was divided by A , but it is implied by the units of discharge in Figure 1).

*We observe that the units of $1/a$ in Figure 4 are given as days, regardless of the value of “ b ”. This is erroneous. Even if the units of $1/a$ were labeled correctly as $1/[L^{(1-b)} * T^{(b-2)}]$, this figure would be problematic. What does it mean to order values along an axis when their units are not identical? Such a figure implies, for example, that $1/a = 2 \text{ m}$ is more than $1/a = 1 \text{ day}$, yet the comparison is nonsensical.*

More importantly, because of the non-physical dependence of “ a ” on “ b ”, no physical interpretation can be made of the relationship between “ a ” and “ b ” from Figure 4. There may be information in the differing distributions of “ b ” between catchments with different land covers, but since “ a ” depends in a non-physical way on “ b ”, it is not physically meaningful to extend this interpretation to also include “ a ”.

Trends in “ a ” will be similarly affected by trends in “ b ” because of the non-physical relationship between these two parameters. To attribute any biophysical mechanisms to any perceived trends in “ a ” without first accounting for the (artificial) dependence on the

trends in “b” is not justifiable. In the manner in which the analysis was done here, only when “b” is constant over time can attribution of some cause to a trend in “a” be attempted.

Lastly, Q_0 is defined as being the characteristic discharge at the start of the recession. It is not stated how this Q_0 determined from a cloud of points consisting of recession curves from a 5-year block. Does Q_0 vary among the 5-year blocks? Is there a trend in Q_0 ? If so, what role might this also have in the perceived trends in “a”?

Our reply has been published on HESSD as Author Comment C4124. For completeness, we repeat it here:

We thank our colleagues David Rupp and Ross Woods (Rupp and Woods for short) for their insightful comments on our paper. They raise several issues to which we would like to reply. These issues can be summarized as:

1. Our definition of a timescale does not provide a single timescale for each catchment.
2. a is not, in general, a recession time scale.
3. The use of the units ‘day’ for $1/a$ in Figure (4) is erroneous.
4. Because of the non-physical relationship between a and b, and a not being a time scale, interpretation of differences in a is nonsensical.
5. Trends in a cannot be understood without first accounting for the dependence on trends in b.
6. Q_0 is ill defined.

For the sake of clarity, we address these issues in a slightly different order, starting with the last one.

Issue 6: Q_0 is ill defined. — Parameter Q_0 was introduced in Eqn (5) as “a characteristic discharge at the start of the recession” (line 9871/3). Although we did mention that T is “the timescale for which half of the initial reservoir storage is depleted” (page 9870/line 21) we evidently failed to mention that these definitions are coupled: $Q_0 = Q(0)$ is assumed to be consistent with initial storage $S(0)$. Several choices can be made regarding the precise meaning of $Q(0)$ and $S(0)$. Is it the storage/discharge at the start of an individual recession event? A characteristic ‘wet conditions’ storage/discharge for that catchment or a characteristic storage/discharge combination for the whole of Sweden? We regret that we have not been more precise here. Since the goal of recession analysis is to study the characteristic response of catchments, the first interpretation is excluded. In the remainder of this reply, we use both the second and the third interpretation: Either Q_0 is, for each catchment, the discharge exceeded 5% of time (Q_5 , representing wet / high flow conditions), or Q_0 is fixed at 10 mm/day for all catchments. We did not look at trends in Q_0 (second interpretation) over time. [update: we define Q_0 now in the paper, in the caption of Figure 4.]

Issue 1: Our definition of a timescale does not provide a single timescale for each catchment. — These two definitions of Q_0 , when used in Eqn (5), both result in a single and unique timescale for each catchment.

Issue 2: a is not, in general, a recession time scale. — We agree with Rupp and Woods that, in theory, neither a nor $1/a$ can be used as a time scale directly, because

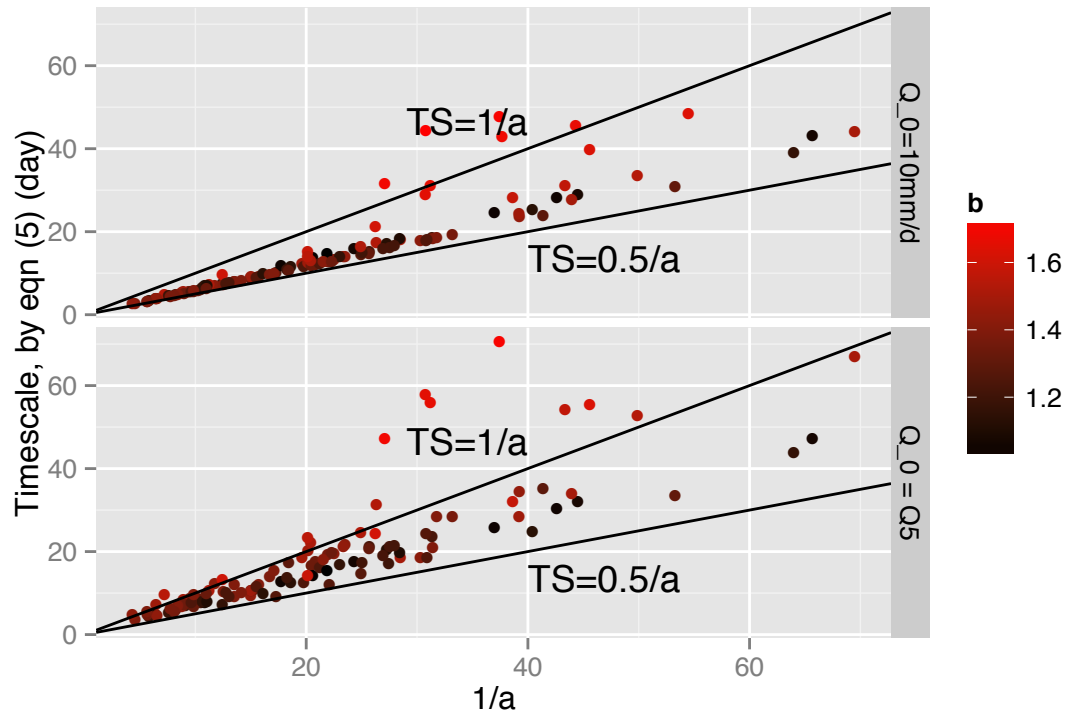


Figure 1

the effect of b and Q_0 in Eqn (5) cannot be ignored. However, in practice, this impact is limited. We used the two interpretations of Q_0 as explained above (i.e. either fixed 10 mm/day, or the 5% exceedance probability discharge per catchment) to compute the ‘proper’ time scale as per Eqn (5) and plotted them against $1/a$ (Figure 1 of this Reply). From these results, it is clear that proper time scale T and its approximation $1/a$ are strongly correlated. For $Q_0 = 10 \text{ mm/d}$, 83% of the variance in T is explained by $1/a$ (linear regression; using the adjusted R^2 ; outliers removed) while for $Q_0 = Q_5$ this is 72%. However, Brutsaert-Nieber type of recession analysis traditionally focus on a and b , and therefore we decided to present a and $1/a$ rather than T .

Issue 3: The use of the units ‘day’ for $1/a$ in Figure (4) is erroneous. — Indeed, as mentioned under Issue 2, the use of the units for the quantity $1/a$ in Figure 4 is erroneous, and a mistake from our side. It will be corrected in the revised manuscript. Still the interpretation of Figure 4 holds.

Issue 4: Because of the non-physical relationship between a and b , and a not being a time scale, interpretation of differences in a is nonsensical. — What we aim to do is to identify how combinations of a and b relate to land use, landscape and climate and how these combinations change over time. Despite any correlation between a and b , and regardless of the meaning of a or b , we do think that there is scope for a cluster analysis as performed in Figure 4: For similar values of a multiple clusters of b are found, and vice versa. The strong correlation of $1/a$ and T , as demonstrated here warrants an interpretation in terms of timescale as long as differences in $1/a$ are pronounced (i.e. taking the uncertainty in the $1/a$ - T relationship into account). In the revised manuscript, we will include this analysis. [update: we show the similarity between $1/a$ vs b ; T vs b and T_0 vs b , in our expanded Figure 4.]

Issue 5: Trends in a cannot be understood without first accounting for the dependence on trends in b. — We agree that much of the trend in a is related to the trend in b. We do not claim that they change independently of each other.

Nevertheless, our results that response time scales have been increasing over time still holds, even after correction for b. In **Figure 2** of this Reply, we show trends in 1/a and T (using $Q_0 = 10$ mm/day to compute the latter). For 1/a, 81 catchments show a significant increasing trend, and for T this is 65, suggesting that indeed part, but certainly not all of the trends in a or 1/a are caused by the trend in b.

Again, we thank Rupp and Woods for their careful reading of our manuscript and the insightful comments they expressed. We are confident that the additional analyses and

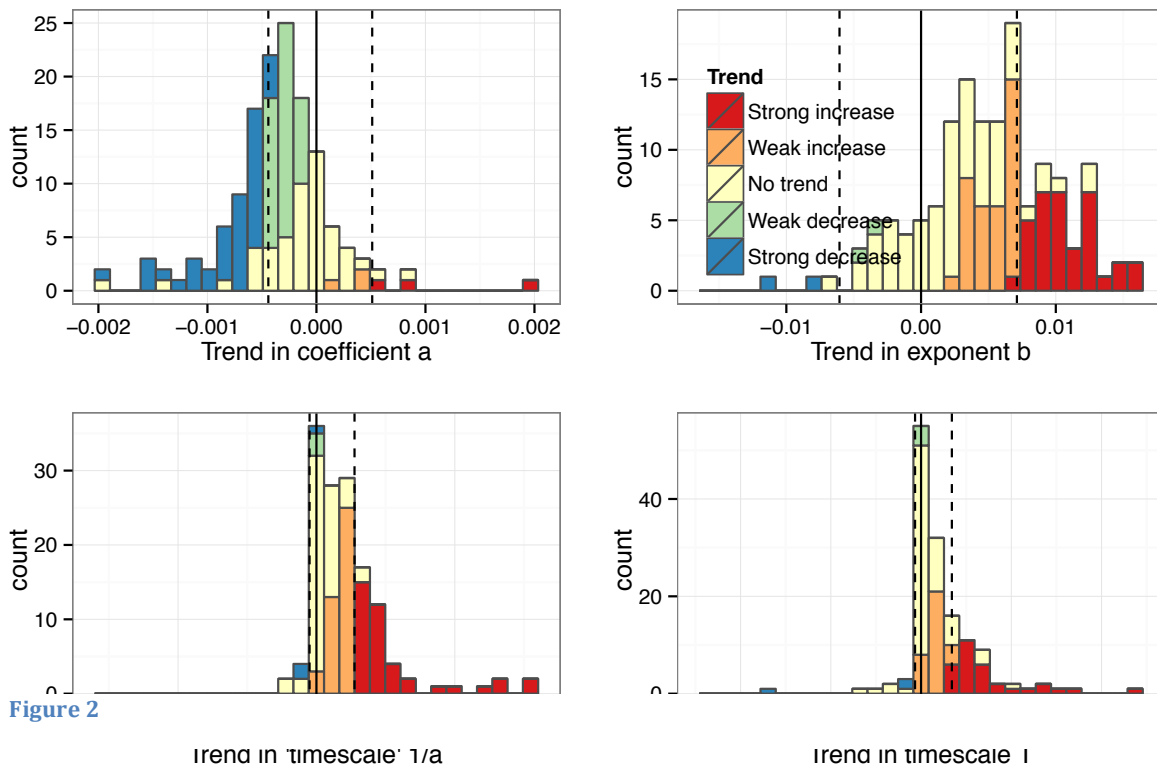


Figure 2

associated discussion, as presented here, will add to the quality of our final revised paper.

Short comment #1b (SC C4256; Rupp and Woods)

In their reply to our short comment, the authors provide a plot (which we refer to as Interactive Comment Figure 1, or IC Fig. 1 for short [Figure 1]) showing the relationship between the characteristic recession timescale T and the recession parameter $1/a$ as estimated from a large number of basins. They argue that because there is a strong linear relationship (high correlation) between T and $1/a$, T can substitute for $1/a$.

We interpret IC Fig. 1 somewhat differently.

First, we note how the slope of T vs. $1/a$, for fixed Q_0 and b , is given by their Equation 5:

$$\text{slope} = \frac{Q_0^{1-b}}{(b-1)} \left(2^{-\frac{1-b}{2-b}} - 1 \right) \quad (1)$$

In the upper panel of IC Fig. 1, where Q_0 is conveniently held constant at 10 mm/day, the points cluster around a line with slope ~ 0.6 . This is a result of most of the values of b falling

between 1 and 1.5 (see Figure 2b), where the slope given by (1) ranges from 0.58 and 0.69. Therefore, the high correlation reflects both the particular shape of the frequency distribution of b and a fixed Q_0 , and as such is not a generalizable result.

However, the lower panel in IC Fig. 1 is the more relevant one given all basins will not share the same “characteristic discharge at the start of the recession” Q_0 . Here there is more scatter between T and $1/a$ (and lower correlation) because Q_0 is also varied by basin. The authors chose to ignore this scatter, even though it shows T varying by roughly a factor of 2 for a given value of $1/a$.

We did not “choose to ignore” that scatter; we simply showed that there is a strong correlation between T and $1/a$.

We believe it is more defensible to characterize these basins by the timescale T and not $1/a$, though this is still not without its problems. For one, it adds difficulty by having to come up with some justifiable manner of deciding upon a characteristic recession discharge Q_0 .

We agree that $T(Q_0)$ is a better timescale characterization than $1/a$, despite its subjective dependence on Q_0 . Therefore, in the revised manuscript, we have included a plot similar to Figure 4, where for a subset of the data (chosen for lowest uncertainty in recession analysis b is plotted against $T(Q_5)$, to show how the general increase in b remains associated with an increase in timescale. We also include a similar plot for the timescale T_0 as defined by McMillan et al (2014).

We are grateful that the authors demonstrated the effect of using T instead of $1/a$ for a given Q_0 . They show already that 20% fewer basins show a trend in T compared to $1/a$ when Q_0 is held constant across all basins.

Still, there are many more basins with T increasing than there are with T decreasing, which was one of our main conclusions.

We emphasize that the use of T instead of $1/a$ still does not guarantee that the effects of the non-physical correlation of $1/a$ and b are removed when examining trends in T within a basin. This is because the particular choice of Q_0 matters.

We agree that this issue has not been brought to closure. However, our use of Q_5 as a measure of peak discharge guarantees some degree of objectivity in our analysis.

Lastly, we still maintain that Figure 4 is inappropriate. Firstly, we ask again: what does it mean to order values along an axis when all the values do not share the same units?

Figure 4 is composed of two components. The first component is the phase portrait of catchments and map pixels in terms of a and b (plotted as $1/a$ vs b) and the identification of land-use related clusters. This plotting and clustering is independent of the ‘unit issue’

Secondly, the common direction of the arrows (lower left to upper right) points to an artifact. As b increases, $1/a$ increases (a decreases), as nicely illustrated by Figure 5, given the y -intercept, $\ln(a)$, is to left of the axis of rotation. Note, however, that $1/a$ can instead decrease (a increase) under the same rotation by a simple conversion of units that moves the y -intercept to right of the axis of rotation! Unless the change in a due purely to the rotation illustrated in Figure 5 is removed, there is no point ascribing any physical significance to a trend in a .

The second component of Figure 4 is formed by the collection of arrows, representing trends in a and b for actual catchments. We agree with Rupp and Woods that indeed a

change in a cannot directly be interpreted as a trend in recession timescale. We present a new **Figure 3**, (Figure 4c–d in the paper) comparing trends in $1/a$ vs b and (left panel) and $T(Q_5)$ vs b (center panel). As can be seen, the general trend towards more nonlinear behaviour and slower recession holds even after the use of T rather than $1/a$. For completeness, we have also computed T_0 , as defined by McMillan et al (2014): $T_0=1/a$ after nondimensionalizing Q using median Q . Again, this gives similar results.

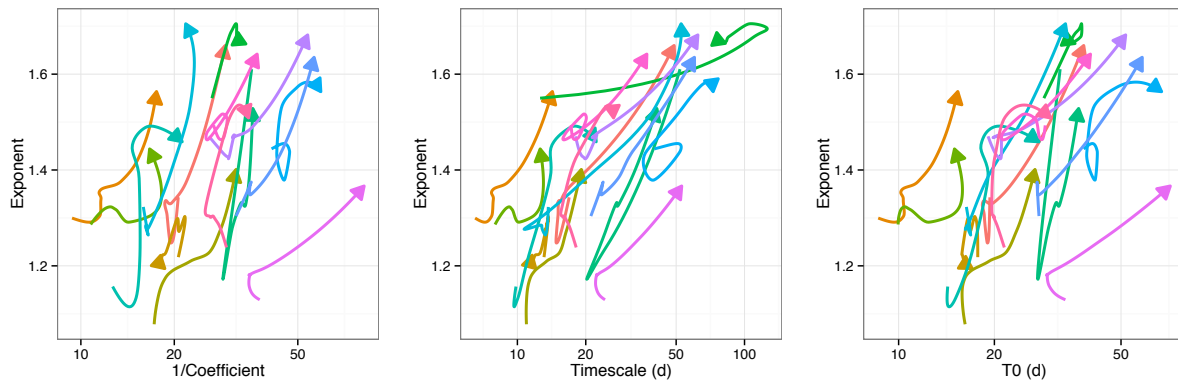


Figure 3: left: b vs $1/a$; center: b vs $T(Q_5)$; right: b vs T_0 sensu McMillan et al (2014)

Short comment #2 (SC C4115; Basudev Biswal)

The research questions raised by the authors are important, and they have made some interesting revelations. Particularly, their results on the relationship between landuse and recession flow properties seem to be informative.

We thank our colleague for his interest in our work.

However, I have some doubts regarding the analytical methods followed by the authors. Below are my comments and suggestions that they may find useful:

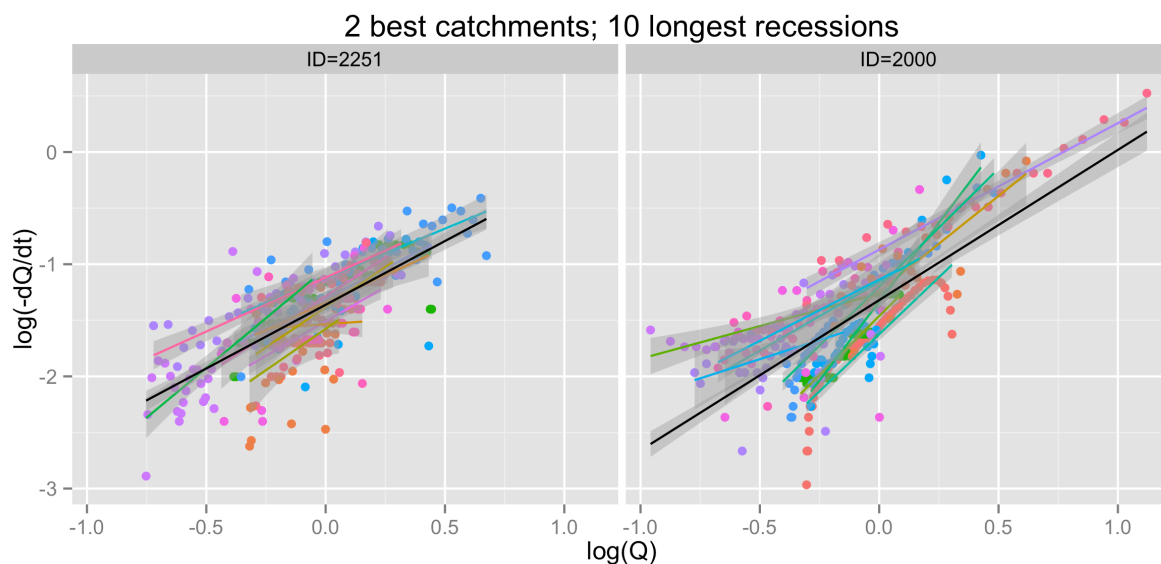
1. I agree with the previous commenters D.E. Rupp and Ross Woods that a plot between the recession coefficient 'a' and the exponent 'b' (Figure 4 in the article) can be misleading because the units of 'a' depends on 'b'. So we won't get any useful information by comparing 'a' values from two recession events having different 'b' values.

We like to refer to our reply to the same comment by Rupp and Woods.

2. The coefficient 'a' of a basin varies significantly across recession events (see, for e.g., Biswal and Marani, 2010; Shaw and Riha, 2012). Note that the variation of 'a' can occur over three orders of magnitude. However, the exponent 'b' does not vary much for a basin; hence, we can use a representative 'b' for a basin assuming that its variation is mainly due to errors in the data. The comparison of 'a' values from different recession events can then be done considering a single value of 'b', in which case 'a' for different recession curves will have the same units. It can be found by integrating the power law recession equation ($-dQ/dt = aQ^b$) that there is a relationship between 'a' and the characteristic discharge Q_n (discharge after n -th day after the recession peak): $a \propto Q_n^{-(1-b)}$ (Biswal and Marani, 2014). This implies that 'a' will decrease with increase in Q_n (which represents initial storage in the basin), and vice versa (note that generally $b > 1$). Therefore if we have to study the effect of catchment properties on 'a', we need to first eliminate the effect of Q_n on 'a'.

Basudev Biswal first notes that in several published cases coefficient 'a' varies across recession events, while 'b' remains stable. We have briefly looked for this phenomenon (Figure1, below), and have to conclude that indeed individual recession events do not align perfectly. We do, however, see little evidence for a systematic shift of recession events having constant 'b' (See below). For one thing, the classic interpretation of a shifted recession powerlaw is due to evapotranspiration (ET), i.e. increasing $-dQ/dt$ for similar Q , which is also called upon by Shaw and Riha (2012). Alternative recession responses to seasonal ET effects are, however, known. In a study in progress, we see for a small catchment elsewhere that the recession power law strongly rotates around a high- Q pivot, having low (and linear) exponent 'b' in summer and high exponent 'b' in winter, suggesting a more complex link between seasonal changes in storage, ET and recession behaviour than described by the papers cited by Biswal. While these phenomena are real, they are in general still mostly poorly understood and we decided to leave this matter out of our analysis. So, we do miss some event-scale analysis and replace it by an overall recession analysis, as is most commonly done. Does this invalidate our interpretations? We do not think so. Even if our 'a' and 'b' values deviate from those for individual recession events, they still approximate the general recession behavior of catchments and are treated as such. Furthermore, our results of significant rotation of recession power laws would be difficult to reconcile with the notion of variable 'a' but constant 'b' as suggested by Biswal

Referee comment #1 (RC 4257; Hilary McMillan)



This paper examines changes in the recession parameters over time for 200 Swedish catchments, and attempts to relate these changes to changes in climate or human impacts on physical catchment properties. This is an interesting concept, and well-suited to HESS.

Thanks.

I will not comment further on the question of flow normalisation, as this issue has been comprehensively covered by the previous reviewers.

OK, see our replies below.

However, I have some comments on the remainder of the paper for the authors to address, particularly focused on results relating to the b values which are unaffected by this issue.

1. Screening

The authors perform a second iteration of screening to remove catchments where b is uncertain when fitted over the whole time series. However, does this in fact remove catchments where b changes significantly over time?

We have checked this by looking at those 95 out of 330 basins that did not pass the $U^* < 0.1$ test (i.e. the second screening iteration). We found that for these basins more than 90% of the individual 5-year intervals had an $U_5 > 0.25$ (the first screening criterion). After excluding these, the basins left had only very little temporal coverage, no strong trends, or both. In the revised manuscript, we made a comment on this.

b values are also subject to uncertainty in the flow series, as I investigated in a recent HESS paper (Westerberg and McMillan, 2015), it would be useful if the authors commented on the likely magnitude of this uncertainty in their catchments, and its potential to impact on comparisons between catchments.

The general methodology used by Westerberg and McMillan (2015) to assess uncertainty in b was not usable for the data studied here, because it involves generation of “equally likely possible realizations of the true [discharge time series]”, generated by a Monte Carlo approach and rating curve uncertainties.

More specifically, Westerberg and McMillan (2015) assessed uncertainty in b in two ways: (1) using hourly vs daily flow data and (2) using all data combined vs. calculating parameters by season and taking the mean.

The first approach is not applicable to the data studied here because hourly data was not available.

We have tested the second approach by looking at the ‘best’ 20 catchments (in terms of uncertainty U^*) and selected the recent data (year 2000 and onwards). a and b were computed using monthly subsets and after rejecting of unreliable monthly b ($r^2 < 0.2$) an average b was estimated. This value was compared with the direct overall estimate of b . For these 20 catchments, the difference between the two varies between 0.02 and 0.30 with a median value of 0.07. Given the total range in b (0.8–2.3), and the general scope of the study, we evaluate this uncertainty to be acceptable.

2. Mechanistic interpretation of recession parameters

The authors discuss in depth the physical meaning of different b values with respect to the type of aquifer represented. However, as discussed in the Clark et al paper already cited, high b values can result from a combination of multiple hillslopes each with lower b value. I would imagine that this could be the cause of catchments containing wetlands having high b , because the wetland is behaving very distinctly from the rest of the catchment. It may also influence the results for changes in b in snow-influenced catchments, where snow areas are acting differently to non-snow areas, and the spatial/temporal patterns of snow are changing over time. Changes in seasonal precipitation patterns may similarly change the relative depths of water in different catchment stores, again changing b . I would like to see the authors comment on how this alternative interpretation of b affects their various conclusions.

Clark et al (2009) showed how for Panola Mountain b scales with catchment area: from $b=1$ for the hillslope to $b=3$ for the 41 ha catchment. For our Sweden data set, we find a very weak overall area dependence ($p=0.02$, but $R^2<0.05$). The effect of catchment size is mostly seen in coefficient a .

We did take snow into account (P_{snow} , Figure 3) in our multiple non-linear regression and we actually found that snow is a very important factor in controlling b , together with open water and temperature. Therefore, we thus accounted for snow in our spatial analyses of b -values of which the dots are shown in Figure 4.

The discussion about various stores within a catchment is, although interesting, outside the scope of our current 'big data' approach.

3. Sections 4.1.2 to 4.1.5

These sections are reporting mainly negative results (i.e. no dependency of recession parameters on various explanatory factors) and could therefore be shortened.

Section 4.1.2., on precipitation is almost one page, but sections 4.1.3. on temperature is only 9 lines, and section 4.1.4 in streamflow is just 7 lines. Furthermore, We don't agree that negative results are a good reason for not elaborating. We also do not agree that the section on precipitation is a negative result, but it confirms the robustness of our approach, as we expect that there is no correlation between precipitation and a/b .

4. Evapotranspiration

The discussion in this section is based on the finding that b is negatively correlated with E/P . However, given that this is due to the fact that both have a strong North/South gradient, it is quite likely not a causative relationship. Please could the authors comment on this.

The reviewer is right that the association between b and E are not necessarily indicative of a direct causal relationship. However the fact that 'both have a strong N/S gradient' is no evidence of the absence of any causal relationship either. The causal links between location (i.e., northing), land use, evapotranspiration and recession parameters are complex, partial contingent and non-unique.

In the revised manuscript, we have now included a brief discussion on this topic: "Note that this association between patterns in E , a and b are not necessarily indicative of a direct causal relationship, but may rather be the result of underlying geographic gradients (climate, soils, land use), that are partly contingent (e.g., geology) and partly interrelated (e.g., land use)"

5. Soil conductivity profiles

The effect of agriculture versus forests on near-surface conductivity profiles is suggested as a cause for changes in b . However, I would expect the main changes in soil conductivity with land use to be in the upper ~1m of soil, which would be typically unsaturated during the main part of a recession period. Therefore, will this really impact on the fitted b value?

The reviewer is right that direct effect of land use changes (e.g., ploughing) on soil structure will predominantly be limited to the upper 1m (or less), although indirect effects (e.g., tile drainage) may have wider/deeper effects on typical groundwater levels. To what extent this zone can be regarded as simply 'unsaturated' remains to be seen. It is (in agricultural areas) not uncommon for shallow groundwater to rise towards the soil surface during periods of prolonged rainfall (witnessed by e.g. pond formation on

agricultural fields). The return to deeper interstorm groundwater levels is the main period of recession, and will be heavily influenced by this upper soil zone.

In the revised manuscript, we now have included a remark on this (in Section 4.1.6): “It should be noted that above mechanisms focus on the upper ~1m, which is commonly unsaturated. Yet, this is the zone which is most relevant for stream flow recessions, because it represents the zone in between storm and inter-storm groundwater levels.”

6. Figure 3

A note that I was interested to see that the fraction of clay soils was one of the most significant predictors of b . In my previous work looking at predictors of b on a smaller scale (McMillan et al., 2014), then a similar index (% high hydraulic conductivity soil) was also the characteristic with the highest predictive power.

Thanks for brining this paper to our attention. We’ve now included a reference to it: “The strong association of exponent b with explanatory variable Clay is in agreement with other studies that, although on a smaller scale, found b related to the percentage of highly conductive soils (Tague and Grant 2004; McMillan et al., 2014)

Short comment #3 (SC C4363; John Ding)

Subject: On the interaction of the Brutsaert and Nieber model parameters

I’m impressed by both the extensive geographical coverage of Swedish catchments and the bold synthesis, from an anthropogenic, a climatic as well as a physiographic prospective, of reams of results from streamflow recession data analysis. For the Brutsaert-Nieber model fitting, the authors use a logarithmic time-derivative transform method expressed by Equation (6), $\log(-dQ/dt) = \log(a) + b \log(Q)$.

In my view, the Discussion Paper can benefit from additional insights into the interaction of exponent ‘ b ’ and coefficient ‘ a ’ from a different perspective of a linearized exact solution below.

The source differential equation shown in Equation (2), $-dQ/dt = aQ^b$, has an exact solution. No references need be cited to prior work, mine included, to show how to solve it. This can be done here, and the solution is:

$$Q^{-(b-1)}(t) = Q^{-(b-1)}(0) + (b-1)at, \text{ if } b < 1.$$

This form of a linear relationship between a power transformed discharge, $Q^{-(b-1)}(t)$, and its elapsed time t , is free of a time-step-size term (dt), thus temporal scale invariant.

The power transform of the discharge data depends solely on $-(b-1)$. On a recession data plot of the transformed discharge versus time, the product of $(b-1)$ and ‘ a ’ reflects the slope of the data points. In the context of the power transform solution method, exponent ‘ b ’ will have to be defined before coefficient ‘ a ’.

We thank John Ding for his insightful comment. The proposed transformation is an interesting one, but unfortunately difficult to test due to the absence of an established method to estimate ‘ b ’ in advance of ‘ a ’, using stream flow data. In his own work on the topic (HESS-D paper [10.5194/hessd-10-15659-2013](https://doi.org/10.5194/hessd-10-15659-2013)) mr. Ding used prior chosen values of ‘ b ’, a procedure that is not appropriate for the current study.

This is in contrast to the conventional method followed by the Discussion Paper, by which both parameters are determined simultaneously, their values valid for the chosen size of the computational time step, which is one day therein. On the latter point, two most recent

examples on exponent 'b' increasing from daily to hourly values are shown in Figure 9 in Westerberg and McMillan (2015), a reference cited by the latter named Referee.

As explained earlier, in an answer to McMillan's comment, we were bound to use the 'conventional' method to evaluate 'a' and 'b' simultaneously, i.e. by plotting $-dQ/dt$ vs Q , using daily time steps because of the lack of hourly data.

Referee report #2 (RC C6004; Anonymous)

The paper presents an analysis of catchment runoff behavior based on the coefficients of the Brutsaert and Nieber [1977] recession slope analysis for numerous Swedish catchments. Both, describing catchment runoff behavior and the use of the coefficients are actually discussed themes and therefore in the scope of HESS. However, describing catchment properties and trends with two coefficients of the recession analysis is a promising approach to catchment characterization. In general, the paper is well organized and presented, but some issues need to be addressed:

Please provide a description of the "strong gradients in climate" and possible gradients in runoff behavior or flow regimes. This would be helpful to assess the setting and your data for readers not familiar with special characteristics of swede.

We have now included a brief quantification of the mentioned gradient (i.e, mean annual temperature ranging from <0 in the North to 8°C in the South (van der Velde et al 2013, their Figure 1C). Gradients in runoff behavior are the topic of the study, and shown extensively in the form of maps of recession parameters.

Furthermore, findings like the increase of 'b' with latitude may be affected by climate. In addition a short description of the catchments, e.g. catchments sizes and distribution (spatial and characteristics) would be helpful.

In the revised manuscript, we have now included min, max and median catchment size.

Are you sure, that the equate use of coefficient 'a' respectively '1/a' to indicate recession time scale in days (e.g. Fig. 4) for linear and non-linear reservoirs is accurate? For non-linear reservoirs 'a' depends on Q_0 , for linear reservoirs not.

See separate discussion on recession time scale in response to the comments by Rupp and Woods. Furthermore, we did not write that a depends on Q_0 for non-linear reservoirs, but rather that T depends on Q_0 . a is just a , and independent of Q_0 .

I miss a description of the selected recession periods, e.g. how many periods did you select for each 5-year subsets. Are the selected recession periods event- or seasonal- based? Do you really have recession times up to 66 days for catchments with 'b' about 1? What are the recession times for catchments with non-linear recessions?

We have simply used all available recession periods remaining after applying the exclusion criteria mentioned in Section 2.2.1. (In the revised manuscript, we now mention this). The number of '66' is not a recession duration, but the time scale $1/a$. Ranges for $1/a$ for other values of b can easily be interpreted from Figure 4.

Minor remarks: Figures 1, 2 and 3 are very small and hard to read and to explore. E.g. Figure 3: the scale-bars are readable only with high magnification. Please ensure readability without magnification.

The small type was partly due to the automatic scaling of submitted figures to the small HESS-D pages. In the revised manuscript, we will make sure text is readable when figures are printed at HESS text width.

Page 9868, line 24: "... catchment catchment ..."

Thanks, fixed.

Page 9872, line 22: "... 0.1 mm day-22 ...": ?

Thanks, fixed.

Page 9880, line 2: "Clay (rank 2)" rank 3?

Thanks, fixed.

Page 9878, line 13: Fig. 2: please specify which part of the figure you refer to (**c** and **d**?).

That's correct. Thanks, fixed.

Page 9883: line 22-23: "... variables. The correlation ..." Page 9884, line 3: "... lead lead ..."

Thanks, fixed.

Student review reports

Student review report #1 (C4476; Mark Wilde)

Introduction

In this paper the a and b values of the (Brutsaert and Nieber, 1977) analysis method are determined with the aim to learn if these values for 200 Swedish catchments differ over a 50 year timescale. By finding the recession behaviour of the parameters they aim to determine if physical properties of a catchment are affected by climate and humans. This is an important topic that is named in several studies. (Troch, 2013) States that an overarching theory of catchment response based on the idea of catchment co-evolution has yet to emerge. Despite the clear results the paper shows, I don't really agree with the description in the title and the fitting and extracting methods used. Finally I would like to see a stronger analysis of the effect of evaporation, possibly in combination with other fitting and extracting methods. In my view, the paper can benefit from a different approach regarding extraction and fitting methods. This might also help diminish the influence of evaporation on the results.

We thank Mark for his interest in this paper, and his careful reading and evaluation. The critical remarks made here are presented and addressed in more detail below.

Title and co-evolution remarks

In my opinion the title does not reflect a research with strong and certain outcome. 'can' is most easily interpreted as 'might be possible, but we aren't all too sure'. I would advise to leave out the 'can' in the title.

Given the fact that catchment evolution is a complex process, and that the investigation of it using the combination of data and mechanistic hypotheses is still in it's infancy, we would certainly not claim that our findings are 'certain'. On the contrary, we believe we've just scratched the surface of the links between catchment co-evolution and hydrological behavior. The use of 'can' in the title therefore feels appropriate.

Furthermore co-evolution is not defined anywhere in the text. It is mentioned that 'correlations between soil, vegetation, atmosphere and humans are taken into account as a measure for co-evolution', yet this is only described at the end of the introduction (p. 9869/2).

The term co-evolution is already mentioned in the first paragraph of the Introduction section, and put in context: "co-evolution between soil, vegetation, atmosphere and humans" followed by a list of papers discussing the topic. Given the intended readership of the paper, and the attention to the topic in the current literature, we assessed the above quote to be satisfactory self-explanatory.

Moreover, except for the human influences on co-evolution that are named in the introduction(p. 9867/13), it might be worthwhile mentioning how hydrological properties are affected by coevolution over what timescales.

We do mention the evolution of soil porosity

Do all co-evolving factors cause noticeable differences within the 50 year measurement period? Can some of the factors be neglected because these small changes are insignificant compared to the entire catchments' properties? I would like to refer to (Harman Troch, 2014) for an elaborated view on this topic.

We do address (in Section 4.2) the evolution of soil profiles from a soil physics perspective, However, the reviewer is right that many questions remain. Again, these are the type of questions that we can now start trying to answer.

Extraction and fitting errors

In contrast with this research, (Biswal Marani, 2010) find that the exponent b for a specific catchment remains fairly constant. Yet, they also state that to avoid severe underestimation of b , recession analysis should be performed separately for each event, rather than binning all recession data together.

See out reply to the similar comment by Biswal.

Although the data in this research has not been binned because of the results of (Stoelzle et. al., 2013), (Biswal Marani, 2014) claim that superimposing of data can also lead to a significant underestimation of b . This effect might be visible in figure 1, E, F and G. It is clearly visible that the data in these plots are not necessarily distributed linearly. For example in figure 1.E, the data points $< 1Q$ show a larger slope than the data points $> 1Q$.

Indeed, this phenomenon is happening sometimes. Due to the many more data points for higher Q , the impact on b is limited.

Another cause for this error in this data might be because (Vogel Kroll, 1992) and (Stoelzle et. al., (2013) both define a recession period as a period of at least 10 consecutive days with a decreasing 3-day moving average. For this research a recession period of at least 5 days is used (p. 9874/23). The difference in assumptions of the recession length between this research and the comparative research of (Stoelzle et. al., 2013) might make the extraction method far less reliable rather than the extraction methods proposed by (Brutsaert, 2008) and (Kirchner, 2009). Further analysis might be required to validate if this assumption was made justly.

There appears to be as many versions of the extraction method as there are papers: Brusaert and Nieber (1977) discard the first 5 days; Zecharias and Brutsaert (1988) perform a sensitivity test and conclude that the lower envelope is insensitive for the

number of days skipped and eventually only ignore the first day after each rain event. Parlange et al. (2001) included every daily discharge measurement following rain. Tague and Grant (2004) do not censor for quickflow and use all declining segments in daily 3-day averaged streamflow. Brutsaert (2008), recognizing that in large basins the raingage network density is inadequate to capture all rainfall events, eliminates from each declining segment in daily rainfall the first 3–4 days and the last 2 days. Kirchner (2009) used all receding data points. We believe that we have already discussed extraction methodology in far more detail than is commonly done. See, for instance our interpretation of the results by Stoelzle et al. We see no ground why our extraction method would be “far less reliable rather than the extraction methods proposed by (Brutsaert, 2008) and (Kirchner, 2009)” nor does the reviewer explain why that would be the case. Requesting a “validation” of the “assumption” (recession duration?) is a bit naïve, since the “true” recession behavior or parameters are unknown, if at all existing.

Effect of evaporation on recession curve

(Wang Cai, 2010) find a very big difference between recession shape and baseflow between summer and winter, likely caused by differences in evapotranspiration. They agree with the fact that precipitation does not have a direct impact on recession slopes, yet they claim that evaporation does. (Federer, 1973) shows great differences in recession curves in transpiring (forested) catchments and cleared catchments without transpiration. Furthermore, (Wittenberg Sivapalan, 1999) shows that evaporation greatly influences the shape of the recession curve in his research. According to above named researches, evaporation cannot be neglected regarding recession curves. This error can be fairly well corrected by usage of a different extraction or fitting method.

While we agree that the impact of evapotranspiration on recession does exist, the exact nature of that impact is not well enough understood to warrant a correction in a big-data approach as we do.

Minor Remarks

p. 9868/24: “catchment catchment”.

Fixed.

p. 9873/9: “DEM” not specified as Digital Elevation Model elsewhere in the text.

Replaced “DEM” by “digital elevation model”.

p.9874/22: “day-22”. Please explain why the recession per 22 days has been used here.

Fixed.

p. 9889/23 “-dQ/dt for higher discharge),” Bracket should be placed between dt and for.

Well spotted. Fixed.

p. 9894/21 “upto” should be ‘up to’.

Fixed.

p. 9907 a, b, c, d, e, f and g are used as capitals in the figure but not in the reference to it.

For some reason the references in the caption were converted to bold lowercase by the Copernicus editorial office. We leave this to them.

Summary

Destouni et al. (2013) showed that hydropower dams and agriculture increased evapotranspiration and reduced river discharge in 9 major catchments in Sweden since 1900. Van der Velde (2013a) build on these results and found evidence for strong increases in evapotranspiration flux of agricultural and forest areas in southern Sweden. Based on these studies this paper aims to determine regional patterns in river recession behavior of 200 Swedish catchments to unravel the natural and anthropogenic controls creating these patterns and changes thereof. They use the Brutsaert and Nieber (1977) analysis method to characterize streamflow recession behavior. The resulting parameter values of a and b , which are obtained through fitting, are used to find spatial patterns and trends in river recession. The hypotheses of this paper states that human modifications to the natural system alter storage-discharge and associated recession dynamics of catchments directly or through co-evolution of soil, vegetation, climate, and landscape which in turn change the annual evapotranspiration and discharge fluxes. Eventually the paper concludes that many of the found trends and patterns in recession parameters could be attributed to various natural and anthropogenic drivers.

We thank Lianne for her interest in our paper, and the excellent summary.

Coastal regions are sensitive to river discharge and/or river water quality stresses. One of the coastal regions which experience those stresses is the Baltic Sea (Darracq et al., 2005; Dargahi and Cvetkovic, 2011). Relating river discharges to landscape characteristics via a regionalization approach is crucial for understanding the cause of these stresses (Van der Velde, 2013a). This paper uses this regionalization approach to take a step towards understanding the causes of these stresses.

We like to emphasize here that our paper is not per se targeted at the Baltic Sea, but rather focuses on changes in catchment hydrology in general.

The paper is mostly well written and the tables and figures are often clear. However, I have some remarks. The first major remark is about the used fitting and extraction methods for the data analyse; the assumption that on all 200 catchment the same methods can be applied is not well-founded.

A second major remark is about the way the power law is fitted through the recession data.

The last major issue has to do with the effect of evaporation on the recession analyse; which seems to be neglected. In addition, I have some detailed and specific comments. I therefore recommend a minor revision before publishing.

All remarks introduced here are addressed below.

General comments

1. The paper concludes that the least variability in estimation of b , y (same conceptual meaning of a) and T ($1/a$) is obtained from the VOG extraction method and the REG fitting method (Appendix A) based on a study of Stoelzle et al. (2013). Indeed this combination of extraction and fitting method did have the least variability. But Stoelze et al. (2013) also suggest paying attention to the extraction of different stages of recession, and also to the physical meaning of different fitting methods (e.g. lower envelopes representing slowly receding streamflow recessions), as they focus on a specific storage-outflow relationship. Stoelze et al. (2013) also concludes that inconsistency found among the methods presents a

limitation for regionalization, because it has shown a wide range of recession characteristics calculated for one specific catchment with particular physical characteristics. This said, a more in-depth study of most suitable methods for this study is therefore required. For example use the climate, land cover, elevation and soil characteristics for each of the analyzed catchment adopted from van der Velde et al. (2013a) to determine the most suitable fitting and extraction method for each catchment. This can be done by grouping the catchments with the same characteristics and use different methods per group to determine which methods fit best by a group of catchments with the same characteristics.

First, see our reply to Mark de Wilde regarding his similar comment.

Despite the useful suggestions made, we would like to emphasize that we already did more to explain our choice of method than other workers, who mostly just pick a method. The in-depth study as suggested might be an interesting endeavor, but is clearly outside the scope of the current paper.

The use of a single fitting and extraction method is directed by the need for an objective approach: if every catchment would be analysed in a different way, results would be more difficult to compare (if only because each and every method introduces its own peculiarities and artifacts, cf our extensive discussion with Rupp and Woods). Also, selecting an 'optimal' method per catchments could be miss-used to exaggerate variability within the data set.

2. In the paper the authors fit a line to the whole cloud of recession data to determine the Brutsaert-Nieber parameters. However, by viewing to individual recession events in a cloud of recession data, Shaw et al. (2012) strongly suggest that the most appropriate way to interpret $dQ/dt-Q$ data points is not to fit a line along an envelope of the data cloud or through the center of the data but to select specific points that are representative of the process of interest. In the paper of this research they are interested in the effects of co-evolutionary processes on the hydrological cycle (e.g. geomorphological cycles). When selecting specific points that are representative for each of the processes the way to unravel the role of climate and humans in landscape co-evolution is easier and more precise.

First, see our reply to similar remarks by Basudev Biswal and Mark de Wilde. Furthermore, geomorphological cycles or processes are not expected to be visible in hydrological data as "specific points that are representative" for these cycles and processes. At most, geomorphology and hydrological behavior may both be the result from catchment co-evolution. We've included some extra citations on this (Tucker et al, 1998; Bogaart and Troch 2006)

3. Several studies have shown that evapotranspiration has a considerable effect on streamflow recession, e.g. Tschinkel (1963), Weisman (1977), Federer (1973). In this paper a seasonal variation is recognized in the recession behaviour which follows the seasonal change. In the discussed paper the effects of evapotranspiration seems to be neglected in the extraction of suitable data points. A solution to this comment, according to Teuling et al. (2009), is to select periods when evaporation (and snowmelt) can be neglected. For the method in which the periods should be selected I would like to refer to Teuling et al. (2009).

See our reply to the similar comment by Mark Wilde. The reference to Teuling et al. (2009) is not clear since recession analysis is not mentioned nor used in that paper.

Detailed comments

1. P.9872, 6-7: *“Seasonal deviations from the wintertime recession curve have been used to measure catchment scale evaporation.” In this study? Not really clear sentence.*

No, by Szilagyi et al., (2007), as mentioned. Given that this paragraph is a brief literature review, we believe this is clear from the context.

2. P. 9866, 8-10 : *“Results suggest that the Brutsaert-Nieber parameters are strongly linked to the climate, soil, landuse, and their interdependencies.” Is this a result of this paper? Because this is something that is already known. (Lyon et al., 2009, Brutsaert, 2008, Sjöberg et al., 2012)*

We believe we show enough new links between explanatory variables, their geographic distribution, and recession parameters, to warrant this formulation.

3. P. 9893 19-22. : *In the last phrase of the conclusion the authors suggest one possible implication of the found results: “One possible implication of these results is that models targeted at long-term prediction of stream flow dynamics should take into account the dynamical nature of catchment properties, especially the feedbacks associated with co-evolution of soils, vegetation and land use.” However, the feedbacks mentioned in this phrase cannot be found in the article. The only mentioned feed-back in the paper is the one whereby an increased precipitation rate may lead in an increased drainage density. But a lack in data on drainage density leaves this potential geomorphological feedback unresolved.*

We explicitly discuss many feedbacks (water management; soil profiles; drainage density). Indeed, the magnitude of some of these we cannot evaluate in a quantitative way yet. We don't believe we make claims that we can, e.g. in the quoted phrase.

4. P. 9866 12-15: *“Many catchments show a trend towards more non-linear behavior, meaning faster initial recession, but also slower recession towards base flow. This trend has been found to be independent from climate change. Instead, we suggest that land cover change, both natural (restoration of natural soil profiles in forested areas) and anthropogenic (reforestation and optimized water management), is probably responsible.” I think the last sentence represented this paper really well. Which brings us back to title of this paper “Stream flow recession patterns can help unravel the role of climate and humans in landscape co-evolution” The title and the sentence in the abstracts is contradicting because it is not known if stream flow recession patterns can help.*

We do not understand this comment. Stream flow recessions can help *exactly* because they are linked to land cover and anthropogenic effects, rather than just climate.

Specific comments

1. P. 9868, 24: *the word “catchment” is used consecutive*

Fixed

2. P. 9884, 3: *the word “lead” is used consecutive*

Thanks, fixed.

3. P. 9866, 3-5 : *“However, due to co-evolution of many of landscape properties more sophisticated methods to quantify future landscape-hydrological model relationships are likely necessary.” Is a vague sentence, better use: “However, due to co-evolution of many landscape properties more sophisticated methods are necessary to quantify future landscape-hydrological model relationships.”*

Thanks for the suggestion. Adapted.

Student review report #3 (SC C4732 (Mathijs Meering))

2 Introduction

Land cover change, both natural and anthropogenic, is suggested to be responsible for changing recession behaviour. Land cover change is characterized by system adaptation and change, towards more optimal ecohydrological conditions. This suggests that landscape co-evolution is at play; landscape characteristics are affected. For example, landscape characteristics that are possibly affected are area, sediment percentage and tree volume.

The student reviewer has misunderstood this: (catchment) area and soil (not: sediment) texture and explanatory variables and not necessarily subject to change. We believe we do not make any claim that the variables mentioned here do change.

More landscape characteristics are mentioned in Table 1 of Lyon et al. (2012). Co-evolution of landscapes is not to be seen on a short time scale. Spatial features do not change directly and may evolve differently in time depending on local or regional conditions. For example, land use changes may take several years to be [unreadable: to have effect on?] on the corresponding soil properties (German,2003; Runyanetal.,2012). Landscape co-evolution could happen through climate change and human activity. The goal of the paper is to determine regional patterns in river recession behaviour, taking into account correlations between soil, vegetation, humans and atmosphere as a measure of landscape co-evolution, and unravel the natural and anthropogenic controls establishing these patterns and changes. In other words, the study aims to show that landscape co-evolution occurs because of changes in climate and human activity through the use of stream flow recessions. The authors use recession behaviour as a tool to show how landscapes adapt to changes in recession, influenced by climate and humans.

3 Summary

This research was conducted in Sweden, because of strong gradients in climate, land cover and human habitation. Also, the discharge of many rivers in Sweden is being monitored daily and there have already been previous studies to build upon (Lyon et al., 2012). Changes in climate or human influences may lead to altered river discharge dynamics. Humans can affect discharge directly (through construction of dams/reservoirs, artificial drainage) and indirectly (through deforestation or other land use changes). Also humans influence the climate, leading to climate change, which will change discharge dynamics. Evapotranspiration has a significant effect on the shape of recession as well (Brutsaert, 1982). Human modifications to the natural system change the storage-discharge relationship and associated recession dynamics of catchments directly or through co-evolution of soil, vegetation, climate and landscape, which changes the annual evapotranspiration and discharge fluxes.

The analysis starts with the conservation of mass-equation:

$$dS/dt=P -E-Q \tag{1}$$

with S as the storage of water in a catchment and P, E and Q as respectively the rates of precipitation, evapotranspiration and discharge (Kirchner, 2008). A catchment receives input in the form of precipitation (P), which is either stored (S) or lost as evapotranspiration (E) or discharge (Q). By studying discharge recessions, using the

powerlaw recession model, information on storage-discharge relationships can be obtained. The powerlaw model consists of the following formula:

$$- dQ/dt = aQ^b \quad (2)$$

Plotting the time derivative of stream flow (dQ/dt) against stream flow (Q) itself will make all of the individual recession hydrographs overlap. A and b are parameters depending on the amount of water stored in the aquifer (Troch et al., 2013) and are obtained through fitting. This best fitted line provides information on storage and discharge. $1/a$ is the recession time scale and b determines the linearity of the plot (with a linear reservoir for $b = 1$). The results show a general decrease in a and an increase in b over time, so slower recession (increased retention) and increasing non-linearity of Swedish catchments over the last 50 years. Each land cover class occupies a well-defined region in the a - b phase-space, which can be connected to mechanistic explanations based on hydraulic and hydrologic process laws. Several patterns and trends in the recession parameters results can be attributed to numerous natural and anthropogenic causes. For some of the cases though the independence to these drivers was verified. The paper contributes to existing literature as it provides more insight in how various natural and anthropogenic changes in land cover alter recession behaviour. Plenty of the papers in the references are either about discharge dynamics, recession behaviour and/or land use changes. In my opinion the aim of the paper is to make a coupling of the properties mentioned above to explain recession behaviour. The title presents landscape co-evolution as the variable that is being explained in the paper, while after reading the paper recession behaviour turns out to be explained, using land use changes as one of the explanatory variables.

This is a nice summary of the paper, although the link between results and title is misunderstood. Exactly because we establish links between climate, land use and recession, one is able to distinguish between the two former based on data on the latter.

4 Concerning points

4.1 Linearity of recession plots

Log-log recession plots such as in Figure 1 are often approximately linear, suggesting a power law relationship between discharge Q and the recession rate dQ/dt :

$$- dQ/dt = aQ^b \quad (3)$$

Here, b is the slope of the best fit line. However, the best fit is not necessarily linear. Even in logarithmic plots there may still be non-linearity. Linear relations like in the first graph of figure 8 of Kirchner (2009) are not always the case. For a linear relation, parameters a and b need to be constant. In this case non-linearity will result in different slopes at different ranges of discharge (Q). Looking at the upper graph in Figure 1 the best fit is a linear line. However you could choose for a non-linear line as the best fit too, with a larger slope b at low values of Q and slope b gradually decreasing with increasing Q . In this case, at different values of Q , the values of a and b are different as well, while these should have been assumed constant. So at different discharge ranges it is possible to have different recession behaviour.

The student reviewer is right that recession plots are not necessarily best described by a powerlaw (i.e. linear fit on log-log transformed data). For the Plynlimon catchments, analysed by Kirchner (2009) this is clearly the case, but these catchments have considerably less noise in their recession data than any other known catchment. Given the quality of the data available to us, it will be difficult to distinguish between a power-

law model and alternative, models. Furthermore, we like to connect to a body of physical explanations that link to the power law model as well. These two reasons are in our opinion sufficient to warrant the use of the power law model in the current study.

In the paper it is presumed that the fitted line through the data cloud of Q vs. $-dQ/dt$ is linear. Is it really a linear relation? If not, this assumption is false, and so are the conclusions drawn from this. To solve this problem, we have to assure that the fitting is independent of the distribution of (or range in) Q . One way of doing this is binning. Binning divides the graph in bins, resulting in multiple narrow ranges of Q . In each of these bins an average value of dQ/dt is taken at a certain Q . Then a line is fitted through these averaged values. This method makes sure that the parameters a and b are constant, making the graph solely dependent on Q .

We are aware of the binning method, as introduced by Kirchner (2009). We are, however, not aware of compelling evidence that this method is 'better' than the alternative methods, given (the quality and properties of) our data. See also our replies to similar comments by Mark Wilde and Lianne de Bie.

4.2 Mismatch title and paper content

In the discussion there is hardly any linkage between the recession parameters a and b and landscape co-evolution. It is mentioned whether recession behaviour of catchments is dependent or independent on variables like temperature, precipitation, stream flow and evapotranspiration. Also values of parameters a and b for various situations are provided, but what these values exactly tell us about landscape co-evolution remains unclear.

The final product of the paper seems to be how strong a variable (f.e. temperature, precipitation, evapotranspiration) is related to recession behaviour. Further explanation of the strength of these relationships and its impact on landscapes is absent.

In Sections 4.1.6. (Land use) and 4.2 (Functional interpretation of trends in recession parameters) we clearly link recession behavior to water management and soil profiles. Both are examples of landscape eco-evolution (land use and drainage co-evolving; vegetation and soil profile co-evolving)

What is even precisely the author's definition of landscape co-evolution? This does not evidently come forward from reading the paper.

See our reply to the similar comment by Mark Wilde

The main focus seems to be on that changes in climate, landscapes and land use are used to explain recession. The title suggests differently: it should explain how humans and climate affect landscape characteristics through the use of recession behaviour. In the conclusion it is mentioned that the relative positions of most of the land cover types in the a - b phase-space are strongly linked to relative positions in a similar "water and energy efficiency" phase-space plot, suggesting that land use, water retention characteristics and energy partitioning are strongly interrelated, and possibly the result of co-evolution of the landscape. Again, co-evolution of landscapes is used to explain recession, instead of the other way around. Rephrasing the title differently would already solve part of these problems. Adjusting the title in such a way that it becomes clear that stream flow recession patterns are to be explained by human activity, climate change and landscape co-evolution.

See our reply to the earlier comment (in the Summary section)

4.3 Leaving out degenerated hydrographs

Continuous stream flow records were analysed to select individual recession events. There are several methods (lower envelope fitting, linear regression, binning) to extract these individual recession events from the stream flow records (Brutsaert, 2008; Vogel and Kroll, 1992; Kirchner, 2009). Once extracted, there are two types of hydrographs: informative and degenerated hydrographs. These are to be distinguished on the basis of the uncertainty in the regression process. The degenerated hydrographs yield unreliable estimates of recession parameters a and b . It is however possible to recover them, but this is not done because of the number of catchments.

We're not sure how the reviewer came to the conclusion that is possible to "recover them".

Reliable recession analysis is not always possible because of anthropogenic controls of stream flow (like dams), so these degenerated hydrographs seem to be (partially) the result of human influences. By leaving out degenerated hydrographs you possibly leave out those catchments with a strong human influence on recession behaviour (i.e. resulting in non-powerlaw behaviour), while judging from the title the role of human activity on landscape co-evolution through recession behaviour is one of the main topics of this paper. Human impact is possibly not completely left out of analysis by not using degenerated hydrographs, but at least for a large portion. Using both informative and recovered degenerated hydrographs might yield different results and therefore may result in different conclusions.

We understand the reasoning here, but unfortunately the proposed approach is not possible. For one thing, many hydrographs did contain more noise and artifacts than normal rainfall-runoff behavior. Therefore, there is no recession behaviour at all.

4.4 Lower envelope

According to Rupp Selker (2005) the data of the lower envelope of a hydrograph, plotted as $\log(-dQ/dt)$ against $\log(Q)$, are specifically those data points without contributions of overland flow, interflow or channel storage. Evapotranspiration affects both the intercept a and the slope b of the hydrograph (Szilagyi et al., 2007). The lower envelope of the data cloud has been taken to minimize the influence of evapotranspiration. By doing this, the contributions of other factors (besides Q) to the hydrograph are minimized. Not taking the lower envelope would result in much larger values, caused by evapotranspiration. Using this lower envelope method does however have some draw-backs. Now that the effect of evapotranspiration is minimized, any conclusions drawn on evapotranspiration will be less reliable. Increased evapotranspiration leads to desiccation of the landscape and increases the available water storage capacity of the soil, resulting in lower and less discharge peaks. It is reasonable to take the lower envelope of a hydrograph, as it decreases the influence of evapotranspiration and parameters a and b are less affected, as mentioned in Szilagyi et al. However, taking the lower envelope yields less importance of evapotranspiration on the hydrograph, thus it is more difficult to say anything about the influence of evapotranspiration on water storage and related discharge dynamics and about the link between evapotranspiration and the re-cession parameters that were obtained from the hydrograph. It becomes even more unreliable because it is unclear how the lower envelope is defined. Which data points are used for determination of the lower envelope? Did they take the lower 10 percent of the data cloud to determine the lower envelope? Or was it the lower 25 percent

We are not certain what the comment on our paper is here. For one thing, we do not use the lower envelope method because it requires a prior value for b (All papers using the method assume b to be 1, 1.5, 2 or 3)

5 Recommendations

Assure that the best fit in the powerlaw model is linear. If non-linear, a possible solution to receive a linear fit is binning. In this situation, parameters a and b can be assumed to be constant.

See our earlier comment.

Title adjustment: Human activity, climate change and landscape co-evolution can be used to explain stream flow recession patterns (or something slightly different).

We prefer our original title, see our earlier replies why.

If the authors want the title to remain the same, it should be clearly indicated what the recession parameters mean to landscape co-evolution. Some examples would already clarify a lot and make these obtained recession parameters more concrete.

See our earlier comments regarding e.g. water management and soil profiles.

Discuss that degenerated hydrographs should have been used to include the impact of humans on recession behaviour. Recovering degenerated hydrographs seems in this case to be a time-consuming process. Indicate in the discussion that the study could have included recovering degenerated hydrographs if more time would have been available, so that catchments with significant human influence on recession behaviour could have been included in this study.

See our earlier reply about this issue. They should and could not have been included.

Specify how the lower envelope is defined. In other words: which part of the data cloud was used as lower envelope? If this is known, it becomes possible to tell to which extent evapotranspiration is of importance to recession behaviour (if of importance at all).

We did not use the lower envelope method.

6 Remarks/Errors

Page 9868, line 24: two times “catchment” → delete one “catchment” .

Fixed

Page 9872, line 13: two times “the” → remove one of these.

Thanks, fixed.

Page 9874, line 22: ... < 0.1 mm day-22 → mm day-1.

Fixed to day⁻²

Page 9883, line 11: ... 97 catchments (34

Fixed (36 instead of 34)

Page 9884, line 3: two times “lead” → only one “lead.

Fixed.

Page 9890, line 9: “... is expected to be result in ...” → “... is expected to result in ...”

Thanks, fixed.

Page 9893, line 14: possible → possibly.

Thanks, fixed.

References

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Stream flow recession patterns can help unravel the role of climate and humans in landscape co-evolution

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Abstract. Traditionally, long term predictions of river discharges and their extremes include constant relationships between landscape properties and model parameters. However, due to co-evolution of many ~~of~~ landscape properties more sophisticated methods are necessary to quantify future landscape-hydrological model relationships ~~are likely necessary~~. As a first step towards such an approach we use the Brutsaert and Nieber (1977) analysis method to characterize streamflow recession behaviour of

5 \approx 200 Swedish catchments within the context of global change and landscape co-evolution. Results suggest that the Brutsaert–Nieber parameters are strongly linked to the climate, soil, land-use and their interdependencies. Many catchments show a trend towards more non-linear behaviour, meaning faster initial recession, but also slower recession towards baseflow. This trend has been found to be independent from climate change. Instead, we suggest that land cover change, both natural (restoration of natural soil profiles in forested areas) and anthropogenic (reforestation and optimized water management), is probably

10 responsible. Both change types are characterised by system adaptation and change, towards more optimal ecohydrological conditions, suggesting landscape co-evolution is at play. Given the observed magnitudes of recession changes during the past 50 years, predictions of future river discharge critically need to include effects of landscape co-evolution. The interconnections between the controls of land cover and climate on river recession behaviour, as we have quantified in this paper, provide first-order handles to do so.

15 1 Introduction

River runoff is a key component of the earth system, performing functions that include energy transfer between the geosphere and the atmosphere, sustaining vegetation growth, transport of sediments and nutrients, and providing drinking water for humanity. Therefore, fresh water has been identified as one of 9 planetary boundaries that define a safe operating space for mankind (Rockström et al., 2009; Steffen et al., 2015; Jaramillo and Destouni, 2015). Key questions in defining this safe

20 operating space are how terrestrial precipitation is divided between evapotranspiration, storage in biomass, soil and subsurface, and river runoff, and how this division is affected by climate change and human actions. Answering these questions means facing the complexity and multitude of interactions between soil, vegetation, atmosphere and humans. Therefore, several recent opinion papers in hydrology called for the use of “Darwinian” approaches that try to summarise the effects of co-evolution between soil, vegetation, atmosphere and humans on the hydrological cycle into general emergent patterns, and use these

emergent patterns to explain the origin of the observed variations (Harman and Troch, 2014; Sivapalan et al., 2011; Savenije et al., 2014; Schaeffli et al., 2011; Troch et al., 2013b, 2015).

Humans impact river discharge dynamics in many ways, either directly (e.g. diversions; dams and reservoirs; artificial drainage) or indirectly (e.g. deforestation; anthropogenic climate change) calling for an integrated socio-hydrological approach (Savenije et al., 2014). Sivapalan et al. (2012) described three avenues through which this human role in the hydrological cycle could be investigated: historical, comparative and process investigation approaches. The credibility of process approaches such as agent-based modelling studies that explicitly describe the effects of human choices and interactions between humans and their environment on the hydrological cycle, critically depends on parametrisations derived from historical and comparative data investigation studies. Thorough (re)analysis of observations in a co-evolutionary context, taking into account all correlations and interactions between soil, vegetation, climate and humans, is thus needed.

In this paper we combine a deterministic “Newtonian” approach to derive and interpret river basin storage–discharge relationships and trends thereof with a “Darwinian” approach that relates these river basin storage–discharge relationships to landscape and climate characteristics. From these emergent patterns we aim to infer the climate and human impact on river basin storage–discharge relationships. We focus on the case of Sweden, because it provides both a strong climatic gradient, a wealth of data and numerous previous studies to build upon. Destouni et al. (2013) analysed river discharge changes in 9 major catchments of Sweden since 1900 (historical investigation approach). They showed that both hydropower dams and agriculture increased evapotranspiration and reduced river discharge. Furthermore, hydropower dams decreased river discharge dynamics, while agriculture increased river discharge dynamics. Building on these results, van der Velde et al. (2013a) related yearly average evapotranspiration derived from 50-year water balances of over 300 catchments in Sweden to catchment characteristics such as land cover, topography and soil type. They found evidence for strong increases in evapotranspiration flux of agricultural and forested areas in the southern half of Sweden, which they related to increased biomass production and improved drainage in both biomes. These results were corroborated regionally through water balance modelling work by Jaramillo et al. (2013).

Based on these studies, we hypothesize that human modifications to the natural system alter storage-discharge and associated recession dynamics of catchments directly or through co-evolution of soil, vegetation, climate, and landscape which in turn change the annual evapotranspiration and discharge fluxes. Focussing on the first part of this hypothesis, in this paper we apply a combination of historical and comparative investigation approaches to quantify landscape, climate and anthropogenic controls on river basin storage–discharge relationships. Specifically, we implement streamflow recession analysis as our analytical tool. Streamflow recessions, i.e. how catchments release water after a rainfall or snowmelt event, are typically analysed based on Boussinesq theory, which has been demonstrated to firmly link observed aquifer or catchment ~~catchment~~-response to an underlying physical model, enabling the interpretation of model parameters (Brutsaert and Nieber, 1977; Troch et al., 2013a). Several studies have shown that these recession parameters change over time due to natural processes such as permafrost thaw (Lyon et al., 2009) and changing groundwater storage (Brutsaert, 2008). However, to date, no studies have investigated how human influence changed the river basin storage-discharge and stream recession dynamics in a regional setting. In this paper we aim to determine regional patterns in river recession behaviour, taking into account the correlations between soil, vegetation, atmosphere and humans as a measure for landscape co-evolution, and unravel the natural and anthropogenic controls creating

these patterns and changes thereof. We seek to empirically test the theoretical links between Brutsaert and Nieber (1977) recession parameters a and b , catchment properties and forcing variables, as introduced below in Sects. 1.1 and 1.2. Special emphasis will be given to link spatial patterns and temporal trends in recession parameters to patterns and trends in external controls. For this, we apply recession analysis to stream flow observations from a large number of Swedish catchments, for the
5 last 50 years.

1.1 Theory

Catchments can be regarded as (bio)physical systems that receive input in the form of precipitation (P) which either adds to the amount of water stored (S), or is lost as discharge (Q) or evapotranspiration (E). All hydrological theory therefore revolves about the water balance equation

$$10 \quad dS/dt = P - Q(S) - E(S) \quad (1)$$

Although Eq. (1) is essentially just a continuity equation, application of it to real-world systems is generally not possible because storage S by itself is not directly measurable and the functions $Q(S)$ and $E(S)$ are often highly nonlinear and depend on many factors, which are not always easily parameterized. Examples include hydraulic architecture on multiple scales (rang-
ing from the porous soil medium, via macropores and preferential flow paths, to the stream network geomorphology) and plant
15 physiological controls of transpiration.

Partly as a means to solve these issues, Brutsaert and Nieber (1977) demonstrated how information on storage–discharge relationships can be obtained by studying discharge recessions, i.e. the period after a rainfall or snowmelt event when water drains from a catchment. By plotting the time derivative of streamflow, dQ/dt , against streamflow Q itself, all individual recession hydrographs overlap and the general recession behaviour can be studied by characterizing the recession data with the
20 power law model

$$-dQ/dt = aQ^b \quad (2)$$

where coefficient a and exponent b are empirical parameters obtained through fitting.

In their analysis, Brutsaert and Nieber (1977) proceed by showing that the power law model Eq. (2) is linked to an underlying hydraulic process based on Darcy’s law and various assumptions. For shallow, flat-lying aquifers with uniform conductivity,
25 the predominantly horizontal free surface groundwater flow can be approximated by the Boussinesq equation, or the linearised version thereof, which for this particular case can be solved analytically, yielding expressions for a while keeping b constant (see Table 1).

The powerlaw recession model Eq. (2) is consistent with a generalized class of storage discharge models, i.e.

$$Q = cS^d \quad (3)$$

30 where S is “free” storage above some threshold S_0 (e.g. field capacity), $c = [a(2 - b)]^{1/(2-b)}$ and $d = 1/(2 - b)$ (Clark et al., 2009), such that the linear recession model $b = 1$ corresponds with the linear reservoir model $Q = aS$.

A useful characterisation of recession dynamics is the time scale involved. For linear reservoirs, $1/a$ is equal to the e -folding time, but for nonlinear reservoirs this is no longer the case. An alternative approach is to define the timescale-time scale for which half of the initial reservoir storage is depleted.

For a linear reservoir ($Q = aS$) the recession equation $-dQ/dt = aQ$ can be integrated to yield $Q(t) = Q_0 e^{-a t}$. Using $S = 1/a Q$ and defining time T such that $S(T) = 1/2 S(0)$ yields

$$T = \frac{1}{a} \ln 2 \quad (4)$$

For non-linear reservoirs ($b > 1$ in Eq. 2), no closed solution for T on base of recession parameters a and b exists. We therefore choose to determine T on base of a characteristic discharge at the start of the recession, Q_0 (consistent with the initial storage mentioned above). After integrating Eq. (2) and again solving for T , we yield

$$T = \frac{Q_0^{1-b}}{a(b-1)} \left(2^{-\frac{1-b}{2-b}} - 1 \right). \quad (5)$$

~~so in both cases $T \propto 1/a$, warranting the use of $1/a$ to indicate~~

An alternative approach was used by McMillan et al. (2014), who scale flow Q by median flow \bar{Q} to obtain nondimensional flow $\hat{Q} = Q/\bar{Q}$. Equation (2) can now be written as

$$-d\hat{Q}/dt = \hat{Q}^b / T_0 \quad (6)$$

where T_0 is a recession time scale at median flow.

Although in theory $1/a$, T and T_0 are different measures, and the units of $1/a$ depend on the value of b , in practice these three measures are strongly correlated (See Fig. 4b–d, discussed later).

1.2 Physical interpretation

Making assumptions on the effective (contributing) catchment area and aquifer depth, Brutsaert and Nieber (1977) in their pioneering work applied results based on the non-linear Boussinesq equation (Table 1) to determine catchment-scale effective conductivity k and drainable porosity f . Already in this first attempt, the results were interpreted in the context of land use as well: one outlier, that had an “anomalously” high value for a (relative to expected values based on drainage density) was “undoubtedly [due] to the fact that that stream drains a large swamp”.

Follow-up studies related a to topographic slope and drainage density (Zecharias and Brutsaert, 1988) or aquifer depth D (Troch et al., 1993). Recession-based estimation of k or k/f appeared to be difficult to compare with values based on soil samples, presumably because catchment-scale hydraulic conductivity is strongly influenced by macropores and other rapid flow paths not captured on the sample scale (i.e., Brooks et al., 2004). For this reason, Lyon and Troch (2007), in a related analysis, for example deliberately choose to apply hillslope-scale conductivity estimates.

Despite these difficulties, applications of the method have been reported for widely varying environments, ranging from virtual catchments (Szilagyi et al., 1998) to humid catchments in the Appalachians (Parlange et al.,

2001), steep, fractured bedrock, semi-arid catchments (Mendoza et al., 2003) and tropical spring-fed catchments (Malvicini et al., 2005). Other studies investigated how recession parameters a and b change with geology (Tague and Grant, 2004), scale (Clark et al., 2009) and climate (van Dijk, 2010) or combinations thereof (Farmer et al., 2003; Beck et al., 2013)(Farmer et al., 2003; Beck et al., 2013; McMillan et al., 2014). At least for some catchments recession intercept a appears to vary throughout the year, in response to catchment-scale water storage in conjunction with spatial heterogeneity (Shaw and Riha, 2012; Shaw et al., 2013; Lyon et al., 2015). Seasonal deviations from the winter-time recession curve have been used to measure catchment scale evapotranspiration (Szilagyi et al., 2007).

Relatively new developments are to interpret changes in recession parameters in terms of changes in the underlying controls or drivers. Brutsaert (2008, 2010) used time series of annual low-flow discharge for catchments in Illinois and the eastern USA to detect a (mostly increasing) trend in groundwater storage within the upstream riparian aquifers. Lyon et al. (2009) applied similar methods, combined with the ~~the~~-linearized Boussinesq equation, to a streamflow record of a sub-arctic catchment to determine temporal trends in a , attributed to a trend in aquifer thickness D , taken as a proxy of effective depth to permafrost. The resulting permafrost thawing rate was in agreement with direct observations. Similar results were obtained for the Yukon catchment (Lyon and Destouni, 2010) and the Lena Basin (Brutsaert and Hiyama, 2012).

15 2 Material and methods

This study is situated in Sweden, which serves as an example country for boreal landscapes. The extensive and long term river discharge monitoring network in Sweden, in combination with strong gradients in climate (mean annual temperature ranging from $< 0^{\circ}$ C in the North to 8° C in the South), land cover and human habitation (Fig. 1; see also van der Velde et al. (2013a), their Figure 1), make this country ideal for studying effects of co-evolutionary processes on the hydrological cycle, as previously demonstrated by studies of Destouni et al. (2013); van der Velde et al. (2013a, b) and Lyon et al. (2009).

2.1 Data

The Swedish river discharge monitoring network (Swedish Meteorological and Hydrological Institute, SMHI, vattenwebb.smhi.se) monitors daily discharge of 316 rivers, all of which were considered for the present study. Data extent varied per catchment. Starting years varied between 1850 and 1998 (median 1947) and ending year varied between 1980 and 2011 (median 2011 as well), allowing us to evaluate human effects on river discharge for at least 50 years. Data coverage is good, with only 3 % of daily values flagged as “missing” by SMHI. The catchment area of each discharge station was reconstructed via delineation from a 30 m resolution ~~DEM~~digital elevation model. Catchments where the reported area by SMHI and reconstructed area matched within 5 % were retained for further analysis (289 catchments, ranging from 3 to 33,000 km² with a median size of 390 km²). Climate (luftwebb.smhi.se), land cover (Corine landuse data), elevation (Landmateriet) and soil characteristics for each of these catchment are adopted from van der Velde et al. (2013a).

2.2 Recession analysis

Continuous stream flow records were analysed to identify individual recession events. Subsequently, Eq. (2) was fitted to the resulting multiple short-duration recession hydrographs summarized in a $-dQ/dt$ vs. Q data cloud.

Because of sometimes strong anthropogenic controls of stream flow (i.e. dams and other hydraulic constructions) reliable recession analysis is not always possible for every location and/or time period. Often, but certainly not always, these cases can be recognized visually from inspection of the hydrographs. In order to minimize the amount of subjective screening, a methodology based on uncertainty analysis was used to select temporal windows that are used for final data analysis.

2.2.1 Recession extraction

Several methodologies to extract individual recession events from continuous streamflow records have been proposed, mainly differing in their approach to distinguish between intrastorm (quickflow) recession and true interstorm (baseflow) recession flow. Proposed solutions to overcome these issues include smoothing of hydrographs (Vogel and Kroll, 1992; Tague and Grant, 2004), skipping over initial phases of recession (Brutsaert and Nieber, 1977; Vogel and Kroll, 1992), final stages (Brutsaert, 2008) and large drops in discharge (Vogel and Kroll, 1992). Stoelzle et al. (2013) compared three recession extraction methods (Brutsaert, 2008; Vogel and Kroll, 1992; Kirchner, 2009) in conjunction with their corresponding parameterisation methods (see below), and all possible combinations. It was found that estimates for recession characteristics like recession time varied over 1–2 orders of magnitude. Their results also suggest that the most robust (i.e. least variable) estimate of b is yielded by the Vogel and Kroll (1992) extraction method (see Appendix A1).

We broke up individual streamflow records in subsets of maximum 5 years long, always starting at rounded dates such as 1 January of 1960, 1965, 1970 etc. For each of these subsets recession periods were extracted using the following constraints (modified from Vogel and Kroll, 1992): a recession period is a period in which both discharge and smoothed discharge (3-day moving average) are decreasing. Steady baseflow tails were removed by clipping off against a threshold (10 % of the range minimum–median streamflow). Also data points corresponding to extremely low streamflow ($Q < 0.1 \text{ mm day}^{-1}$) or recession ($-dQ/dt < 0.1 \text{ mm day}^{-2}$) were excluded. Only-All recession periods of at least 5 days were retained.

2.2.2 Fitting parameters

In their original development of the method, Brutsaert and Nieber (1977) note that evaporation during recession flow leads to higher values of $-dQ/dt$ for a given value of Q , and propose to fit Eq. (2) to the lower envelope of the Q vs. $-dQ/dt$ data cloud, which in their application is fitted by eye. Brutsaert and Hiyama (2012) further add that the use of a lower envelope yields, for a given $-dQ/dt$, the maximum value of Q , ensuring that the entire catchment is contributing.

Later applications recognized the possibility of data errors and allowed 5 % (Brutsaert, 2008) to 10 % (Zecharias and Brutsaert, 1988) of the data points to be below the lower envelope, and use (non)linear regression as a more objective alternative to the fit-by-eye envelope approach (Zecharias and Brutsaert, 1988; Vogel and Kroll, 1992; Parlange et al., 2001; Tague and Grant, 2004; Lyon et al., 2009; Lyon and Destouni, 2010).

For larger catchments in hillslope terrain, Brutsaert (2005) suggested that the power law Eq. (2) should be fitted through the entire data cloud (i.e. not using a lower envelope), because heterogeneity in the subsoil likely overshadows the effect of evapotranspiration.

Kirchner (2009) used an alternative approach to noise and errors in discharge data by binning together individual hourly data points in ranges (“bins”) of Q , and computing average Q and dQ/dt for each bin. Lyon et al. (2009) used this approach to validate their method (nonlinear fitting of Eq. 2) while Krakauer and Temimi (2011) use it to analyse Q -dependent recession behaviour.

Again looking at the results of a methodological comparison (Stoelzle et al., 2013, see also Appendix A1), it is suggested that the most robust estimate of recession parameters is yielded by linear regression. Based on this interpretation, and above arguments, we also choose to use linear regression, rather than a lower envelope or binning.

Therefore, each 5 year time series resulted in a set of Q vs. $-dQ/dt$ recession data points through which Eq. (2) was fitted. We followed common procedure by not fitting the nonlinear model but instead fitting the log-transformed model

$$\log(-dQ/dt) = \log(a) + b\log(Q) \quad (7)$$

using simple linear regression with ordinary least squares to obtain estimates of parameters a and b .

2.2.3 Screening

As outlined above, suitability of stream flow data for recession analysis varies with time and space. An additional screening step is used to distinguish between “informative” hydrographs, yielding useful estimates of a and b , and “degenerated” hydrographs, yielding unreliable estimates of a and b . We distinguished between these cases on the basis of the uncertainty in the regression process. Alternative methods exist to potentially recover degenerated hydrographs (e.g. Rupp and Selker, 2006a) but, given the number of catchments and the daily resolution of the data available, we opt for this screening approach.

A common way of summarizing the fit of regression models is based on the computed coefficient of determination, R^2 ; however, we regard this approach as unsuitable because of the dependence of R^2 to the regression slope b (a slope $b = 0$ always corresponds to a R^2 of 0, even if the fit is perfect).

Instead, we used the uncertainty U in the estimation of b , as quantified by the 95 % confidence interval of b (Helsel and Hirsch, 2002). Based on the highly skewed and long-tailed distribution of U per 5 year period, U_5 , a value of $U_5 = 0.25$ appeared, based on visual inspection of the data cloud and the fitted line, to be an appropriate threshold between the suitable and unsuitable data for further analysis.

A second iteration of screening was performed by gathering, per catchment, all recession data for accepted 5-year periods (i.e. $U_5 < 0.25$) and fitting an overall power law model, Eq. (2). Again, for every catchment the associated uncertainty in b over the whole time series, U_* , was computed. The distribution of U_* was again skewed and long-tailed, suggesting a threshold of $U_* = 0.1$.

Summarizing, only 5 year intervals with $U_5 < 0.25$ for catchments with $U_* < 0.1$ are retained. This resulted in a reduction of the original 316 catchments to 220 catchments, for which static (overall) a and b are estimated. (see Fig. 1 for examples). [The](#)

2.3 Trend analysis

The occurrence of trends in Brutsaert–Nieber parameters a and b were analysed by computing a and b for all accepted ($U_5 <$
5 0.25) non-overlapping 5-year intervals, and performing a linear trend analysis, using a rather loose $p = 0.1$ as a threshold for significance of trends in either a or b . Only those catchments were considered that have at least 50 % accepted 5-year intervals coverage since 1960. This was the case for 141 out of 220 post-screening catchments.

2.4 Attribution to catchment properties and external forcing

Many of the catchment characteristics are highly correlated. For example the fraction of agriculture is correlated to the fraction
10 of clay inside the catchments for these Swedish catchments. These correlations are partly the result of co-evolution of soil, vegetation, atmosphere and humans (for example, humans prefer agriculture on fertile clay soils) and prevent unique identification of the controls on river discharge recession via correlating the catchment discharge recession parameters to other catchment characteristics. To account for this nonuniqueness, we applied an ensemble regression approach to unravel the landscape, climate and anthropogenic controls on river discharge recession. This set-up consists of three steps. First, we created
15 a large ensemble of unique multiple regression models that all relate the empirical recession parameters a and b to catchment characteristics (details are given in Appendix A2). Secondly, the entire ensemble of multiple regression models was used to regionalize parameters a and b over entire Sweden on a $10\text{km} \times 10\text{km}$ grid revealing their regional patterns and uncertainty (van der Velde et al., 2013a). Thirdly, we related these regional patterns back to patterns in catchment characteristics and changes thereof (if available), linking observed trends in river discharge recession to potential drivers.

20 3 Results

3.1 Recession analysis

3.1.1 Characteristic parameter values

For all catchments, values for Brutsaert–Nieber coefficient a ranged from 0.012 to 0.23, with 90 % of all a values between
0.018 and 0.13, and 50 % between 0.029 and 0.067. Values for exponent b ranged from 0.50 to 2.1, with 90 % of all b values
25 between 0.84 and 1.7 and 50 % between 1.1 and 1.4 (Fig. 2a and b). For $b \approx 1$, catchments behave like a linear reservoir and $1/a$ can be interpreted as a recession time scale. Out of the 220 catchments, 71 have values which are approximately linear (b ranging from 0.9 to 1.1). For these, $1/a$ varies between 11 and 66 days (median 28.4 days).

3.1.2 Trends

The distribution of estimated trends is approximately normal, with a general tendency of decreasing a and increasing b (Fig. 2)-
c and d). For parameter a , 82 out of 141 (60 %) catchments showed a significant decreasing trend, while a significant increasing trend in b was found for 70 out of 141 (60 %) catchments. Although increasing a and decreasing b trends are found, most of
5 them are not significant at the $p = 0.1$ level.

The median significant decreasing trend in a is -0.00044 , which over a period of 50 years suggest a total change in a of -0.022 . For the case of linear reservoir catchments, with median recession time scale $1/a$ of 28.4 day, as described above, this means an increase from ≈ 22 to ≈ 48 days. The median significant increasing trend in b is 0.0071 , which over 50 years suggest a total change in b of 0.35 , which is almost a third of the typical range for b of 1 to 2. Note that these change magnitudes are
10 for those locations where change does occur, i.e. these are not country-scale overall change magnitudes, which would require a different approach to assess.

Combined together, these results suggest a progressive change towards slower recession (or increased retention) and increased non-linearity of catchments throughout Sweden during the last 50 years.

3.1.3 Spatial distribution

15 The pattern in the spatial distribution of recession parameters (220 catchments) generally follows a north–south gradient: a values are generally high in southern Sweden and low in northern Sweden. For b this pattern is reversed (Fig. 2e–f). For trends in a and b the picture is less clear (g–h). The majority of trends in a are either stable (i.e. no significant trend), or decreasing, without a clear spatial pattern. The few catchments with increasing trends are all located in southern Sweden. For b , the picture is not completely similar. While southern Sweden is characterized by mostly stable or weak increasing b , northern
20 Sweden is mostly weak and strong increasing. The few decreasing trends are scattered across the country.

3.2 Attribution

3.2.1 Spatial explicit correlation

The results of the attribution, shown in Fig. 3, revealed that Brutsaert–Nieber coefficient a is best predicted from the lake fraction within catchments (“Open water”), catchment area (“Area”) and total annual precipitation (“Precip.”). Maximum
25 $R^2 \approx 0.8$ for a is approached with as additional variable the area fraction with slopes exceeding 10 % (“%slope > 10 %”).

Brutsaert–Nieber exponent b was found to be best explained from open water, the amount of precipitation that falls as snow (“PSnow”), the fractional presence of clay soils (“Clay”) and the average yearly catchment temperature (“Temp”). Maximum $R^2 \approx 0.7$ is reached when 4 additional variables are added: the fractional area covered by rocks (“Rock”), slopes exceeding 10 %, slopes exceeding 5 %, and the fractional coverage of wetlands (“Wetlands”).

It should be noted that many variables are strongly correlated with each other. Since the method used favours unique information carried by variables, typically only one of a set of strongly correlated variables is picked up and gets a high presence. One example is Clay (rank 23) which is favoured above Agriculture (rank 13).

All explanatory variables can be loosely classified as either *Terrain* (Elevation, Slope), *Climate* (Temperature, Precipitation, Snow, Degree days (DD), Temperature seasonality index (TSI), Precipitation Seasonality index (PSI)), *Land Cover/Use* (Open water, Wetlands, Agriculture, Forest, Natural Open), *Soil* (Clay, Rock, Sand, Till, Artificial, Peat), and *Other* (Catchment Area). There is no clear ranking of these categories in terms of explanatory power (Kruskal–Wallis test; $p = 0.72$), the largest difference being Climate ranking slightly above Terrain (Wilcoxon test; $p = 0.25$).

Regionalisation of $1/a$ and b (Fig. 3) yielded only locally varying patterns for $1/a$, while b also shows a clear north–south gradient likely related to temperature and/or snow. However a similar north–south pattern could also arise from the fraction of wetlands (Fig. 1) that follow a similar pattern.

Ensemble predictions for $1/a$ and b are robust, having a (ensemble) coefficient of variation of mostly < 0.2 . Exceptions are the high North and *within* some large lakes (where the model assumptions break down).

3.2.2 Phase-space land use clusters

Finally, to unravel the controls on the recession parameters, for all the $10\text{ km} \times 10\text{ km}$ grid cells of our regionalisation maps (Fig. 3), the $1/a$ values are plotted against corresponding b values, with trends superimposed. These “phase diagrams” are analysed by highlighting major land cover types, highlighted as 80 % probability contours (Fig. 4). The general pattern is that most 80 % landcover contours lie along a diagonal where $1/a$ and b are negatively correlated (such that a and b are positively correlated).

It has been found that Natural Open landscapes have the shortest recession time scale (i.e. drain the fastest) followed by Agriculture, Wetlands and Forest, and finally Open Water, which is slowest (Table 2).

At the same time, Open Water has the lowest range in Brutsaert–Nieber exponent b , followed by Forest, Agriculture, Natural Open and finally Wetlands, which behave the most non-linear (Table 2).

Trends are all in the same direction of $1/a$ and b both increasing.

4 Discussion

Overall, our results regarding ranges of Brutsaert–Nieber parameters a and b compare well with values reported in the literature. Here, timescale $1/a$ varied mostly between 11 and 66 days. This range is slightly low, compared to the typical range of 45 ± 15 day as reported by Brutsaert (2008) for large river basins, but their result was obtained using a lower envelope method, which by design results in lower a and hence higher $1/a$. Also, our result of exponent b varying mostly in the range 1.1–1.4 corresponds well with ranges for b reported in earlier studies (Wittenberg, 1999; Troch et al., 2013a).

4.1 Mechanistic interpretation of recession parameters

Based on theoretical arguments (Sect. 1.1) and previous applications of the Brutsaert–Nieber framework (Sect. 1.2), many more detailed interpretations of the results can be made, each linked to individual natural or anthropogenic controls.

4.1.1 Landscape

5 Different dominant land use types (Agriculture, Forest, Natural Open, Wetlands and Open water) occupy distinct regions in a b vs. $1/a$ diagram (Fig. 4). This can be interpreted with the help of the available set of physical processes operating in various landscapes (Table 1).

Lowest b values (0.7–1.3) are found for open water. The clustering around $b = 1$ suggest that for these catchments the linear-reservoir type behaviour might be influenced by the effects of open water related hydraulics ($b = 1$ –1.3 for open channel flow; 10 $b = 1.33$ for weirs), rather than hillslope subsurface flow dynamics ($b = 1.5$ –2). The corresponding $1/a$ values are largest of all land use types suggesting longest recession time scales, which is consistent with the large volumes stored in surface water reservoirs.

Forests have b values roughly ranging from 1.0–1.5, which is consistent with classic physical models as linear reservoirs ($b = 1$) or flat-lying aquifers in homogeneous substrate ($b = 1.5$). $1/a$ values are intermediate, meaning faster drainage than 15 for open-water dominated catchments, but slower than for agricultural and natural open areas.

Agricultural areas have a narrower range in b values, roughly between 1.1 and 1.5, again consistent with flat homogeneous aquifers or linear reservoirs. Values for $1/a$ ranging from 7 to 17 day are among the lowest values compared to other land use types. A possible explanation for this is the presence of artificial drainage which is commonly applied in Sweden for fast drainage of excess water after rain storms (e.g. Ulén and Jakobsson, 2005). From Table 1 it follows that a high drainage density 20 and a high conductivity is related to low values for $1/a$.

Natural Open areas have similar relatively short recession time scales as Agricultural areas, but with a larger range, and higher b values, 1.4 to 1.8. High b values are characteristic for soils with saturated hydraulic conductivity decreasing with depth: exponential profiles result in $b = 2$ (Troch et al., 1993) while power-law profiles result in b ranging from 1 to 2 (Rupp and Selker, 2006b). These type of soils are commonly found in upland regions with in-situ weathered soils.

25 Wetlands have slightly higher b values (1.5–1.9) and smaller a values (slightly higher $1/a$ values), suggesting slightly more nonlinear behaviour and slower drainage than Natural Open areas. This is consistent with the water retention effect of wetlands shown earlier for Sweden (Lyon et al., 2012). The range of b values is consistent with both channel flow hydraulics and wetland peat soils where, due to compaction, hydraulic conductivity decreases with depth, causing b up to 2.

Interestingly, the 80 % contour lines for Open Water and Wetlands do not overlap at all, suggesting that these land cover 30 classes are governed by different, mutual exclusive, physical mechanisms, e.g. “constant” low-resistance flow in channel networks, vs. high-resistance overland flow in wetlands that can be seen as an surface extension of the vertical soil conductivity profile.

The strong association of exponent b with explanatory variable Clay is in agreement with other studies that, although on a smaller scale, found b related to the percentage of highly conductive soils (Tague and Grant, 2004; McMillan et al., 2014).

4.1.2 Precipitation

Using annual precipitation data for 270 catchments, it is clear that precipitation has increased: averaged over all catchments there has been an increase of 5.9 % since 1960 ($4 \text{ mm yr}^{-1} \text{ yr}^{-1} p \ll 0.01$). On the catchment scale, 173 out of 270 catchments (64 %) have experienced a significantly ($p < 0.05$) increased annual precipitation, while for the remaining 97 catchments (34.36 %) no significant trend has been detected. Zooming in on seasonal time scales, this picture changes: for the winter months, only 22 catchments (8 %) show a significant increasing trend, while for the summer months this is 158 catchments (59 %). The increase in annual precipitation has thus predominantly been due to increased summer precipitation.

Precipitation rate (P) has a strong effect on hydrological statistics such as mean or peak discharge, but it is not present in any of the a/b formulae (Table 1). This by itself suggest that changes in precipitation will cause a shift along the power law curve Eq. (2) rather than a transformation of the curve itself. It is therefore not expected that recession parameters are correlated with annual precipitation rate. Although annual precipitation rate was found to be an important explanatory variable for recession intercept a , this result is mainly for precipitation *in conjunction with* other variables. ~~the~~The correlation coefficient for annual precipitation as a *single* explanatory variable is close to 0, confirming the expected independency.

Similarly, *changes in* recession parameters are not expected to correlate with changes in annual precipitation rate. Indeed, no significant correlations ($R^2 > 0.1$) have been detected between trends in (seasonal) precipitation and trends in recession parameters a and b , suggesting that trends in recession behaviour of catchments are independent of precipitation.

On the other hand, higher precipitation rate might ~~lead~~lead, *ceteris paribus*, to an increased storage and generally higher groundwater levels. Depending on the vertical hydraulic conductivity profile, and location of macropores, this may trigger faster flow paths and thus an increased total transmissivity. For linear reservoirs ($b = 1$) or flat Boussinesq aquifers ($b = 1.5$), there may be, through increased effective k , an effect on a (Table 1), while for TOPMODEL-type nonlinear reservoirs ($b = 2$) any effects might be built-in already in the associated recession model, and therefore not be visible. If such a precipitation–storage–conductivity mechanism would be operative, one would expect a relationship between annual precipitation rate and recession parameter a , which is stronger for lower values of b . However, since the correlation between a and precipitation as a single explanatory variable is close to 0, there appears to be no evidence for such a mechanism, either because this hypothesis is false, or because it is linked to event-scale precipitation, which was not analysed here.

A similar mechanism would link high storm precipitation rate to occurrences of overland flow and other threshold-exceeding mechanisms, suggesting a different drainage behaviour under wet (i.e. high-flow) conditions than under normal conditions. Although overland flow and similar mechanisms are beyond the Boussinesq interpretation of Brutsaert–Nieber diagrams, they should still be visible within these diagrams if there recession behaviour would be markedly different from that of Boussinesq recession. However, no compelling evidence has been found that recession behaviour, as observed, cannot be captured within a single power–law relationship. Furthermore, the trends of increasing exponent b and decreasing a suggests a stronger dichotomy between wet-conditions recession rate and dry-condition recession rate, i.e. the range in $-dQ/dt$ increases.

On the long time scale, an increased precipitation rate may result in an increased drainage density, due to feedbacks between hydrological regime and geomorphological processes (e.g. [Tucker and Bras, 1998](#); [Bogaart and Troch, 2006](#)). The resulting increased total stream length L may be associated with higher values for a (Table 1). This suggests that high-precipitation landscapes have higher a values and similar b values, compared to otherwise similar low-precipitation landscapes. Again, a and annual precipitation were found to be uncorrelated. Unfortunately, reliable direct data on drainage density was not available, leaving this analysis of a potential geomorphological feedback unresolved.

4.1.3 Temperature

For temperature, a similar picture arises as for precipitation: 96 % of all catchments show a warming trends on the annual time scale, and none a cooling trend (see also Saaltink et al., 2014). For the seasonal time scales, these percentages are 23 % (winter) and 73 % (summer). Rising temperatures have thus been due to warmer summers mainly.

Again, trends in (seasonal) temperature (where significant) have been compared to trends in recession parameters a and b . In none of the cases we found a correlation coefficient $R^2 > 0.1$, which suggests that trends in recession behaviour of catchments are independent of temperature.

4.1.4 Streamflow

Trends in recession parameters a , b and T have also been compared to trends in streamflow magnitude parameters. These parameters include indicators for baseflow, (Q_{90} , specific discharge which is exceeded 90 % of time), mean conditions (Q_{50}) and peak flow (Q_{10}). As with climate, trends in these streamflow statistics (if any) were not correlated to trends in recession parameters (all $R^2 < 0.1$). This suggests that trends in recession behaviour captures unique information not present in traditional flow statistics.

4.1.5 Evapotranspiration

For evapotranspiration (E), multiple mechanisms can be considered. First, on the annual time scale, increased E may, ceteris paribus, lead to desiccation of the landscape and an increase of available water storage capacity within the soil. This increased buffer capacity results in less and smaller discharge peaks. Because no effect of a and b as such is expected, one expects that changes in annual E results in a shift along the Brutsaert–Nieber curve, which itself remains unaltered. This is the same mechanism as outlined above for precipitation, suggesting that there is no relationship between annual E and the Brutsaert–Nieber recession parameters. Average actual evapotranspiration rate E has been computed for 138 catchments where both precipitation data and sufficient stream flow data were available to determine the water balance. E (as fraction of annual precipitation, E/P) and recession coefficient a are weakly correlated ($R^2 = 0.11$; $p < 0.001$) but E/P appeared to be negatively correlated to recession exponent b ($R^2 = 0.27$). This is consistent with the spatial pattern of low b values and high E rates in southern Sweden, as found by van der Velde et al. (2013a), who linked these high E rates to the intensive agriculture and

many lakes found there. Thus, recession behaviour is more strongly ~~related to evapotranspiration than to~~ associated with evapotranspiration than with precipitation.

Note that this association between patterns in E , a and b are not necessarily indicative of a direct causal relationship, but may rather be the result of underlying geographic gradients (climate, soils, land use), that are partly contingent (e.g., geology) and partly interrelated (e.g., land use)

As with precipitation changes in annual E were not expected to be linked to trends in Brutsaert–Nieber recession parameters. Unfortunately, there was not enough data available in this study to warrant a comparison between catchment-scale changes in E rate and recession parameters. However, van der Velde et al. (2013a) found that on average, precipitation trends are $\approx 2.9 \text{ mm year}^{-2}$ ($0.4 \% \text{ year}^{-1}$) while E trends are $\approx 1.6 \text{ mm year}^{-2}$ ($0.5 \% \text{ year}^{-1}$), resulting in a fairly stable ratio $E/P \approx 0.4$ (increasing with only $0.1 \% \text{ year}^{-1}$). Analysing spatial patterns of change in E/P , van der Velde et al. (2013b) found increases in this ratio mostly associated with agricultural land use in southern Sweden (due to increased water use efficiency), where b values are relatively low (due to low relief and homogeneous soils). Looking at these results on their own merit (b negatively correlated with E/P , E/P either increasing (southern Sweden) or stable), one may reason that the effect of E/P on b should be a stable or decreasing trend in b , which is inconsistent with the main finding of increasing b . However, a more detailed look into the relation between trends in recession parameters vs. absolute values (Appendix A4) shows that the increasing trends in b are mainly associated with those catchments that already have a high value of b . Since the slight increase in E/P is mainly found in the south, where b is generally low, this more detailed look forces one to conclude that the slightly increased E/P (associated with low b) is not in direct contradiction with increased b (associated with high b). Thus, no evidence has been found that trends in E are correlated to trends in recession parameters.

Originally, Brutsaert and Nieber (1977) reasoned that, when similar stream flow events are compared (i.e. similar Q), those events that occur under increased levels of E suffer from increased loss of water, and hence are characterized by a stronger recession, or higher $-dQ/dt$. Therefore, their data analysis method used only the lower envelope of the $-dQ/dt$ vs. Q cloud. As explained in Sect. 2.2, we follow Brutsaert (2005) and fit Eq. (2) through the whole data cloud. This way, stronger/increased (decreased) E would result in an upward (downward) curve of Eq. (2), suggesting that E is positively correlated with recession parameter a . Indeed, as explained above, correlation between E/P and a is very weak but significant ($R^2 = 0.11$; $p < 0.001$).

4.1.6 Land use

Land use change comes in many forms, which can be clustered on functional terms. A change in vegetation cover has mainly effect on (potential) E , discussed above. Land management from a hydrological context can be described in terms of artificial drainage. Several (competing) mechanisms can be thought of, each focusing on either a or b .

First, artificial drainage in the form of tile drainage or an extended network of shallow ditches can be expected to have a positive effect on effective conductivity k , while ditches artificially extend the drainage network L . Table 1 states that for flat-lying Boussinesq aquifers (for which $b = 3/2$), a is proportional to $k^{1/2}$ and L . Although such closed-form relations between a and L are not known to us for other cases, we do expect that ~~artificial~~ artificial drainage leads to higher values for a . Because

no direct data on drainage extent was available, agricultural land use was used as a proxy. Indeed, agriculture has the shortest recession time scale, i.e. highest values of a (Fig. 4).

On the other hand, artificial drainage leads (by design) to a lower groundwater level, and hence to a more pronounced unsaturated zone. For shallow ground water levels, drainable porosity (specific yield) f is strongly dependent on groundwater depth: $f = 0$ when ground water is at the soil surface, and increases with ground water depth until a soil dependent constant value is reached. According to Table 1, using the equations for Boussinesq aquifers, a is proportional to $1/f$. If this mechanism were to be dominant, artificial drainage should lead to smaller values for a . Because, as discussed above, agriculture is associated with higher values of a , this mechanism seems to be small or absent.

Agricultural land use is commonly associated with homogenized soils. In general, values for b are related to the vertical profile in soil hydraulic conductivity (Table 1). For flat-lying aquifers, $b = 1.5$ for homogeneous soils (uniform k profile) but when hydraulic conductivity increases with depth according to a power law b may increase to 2. For sloping aquifers a similar patterns arises, although with a wider range in b : $b = 0$ for steeply sloping aquifers with uniform k to $b = 2$ for both a power-law and an exponential decreasing conductivity profile. Therefore, agricultural catchments are expected to have values for b near their lower limit. As shown in Fig. 4, the 80 % contour for Agriculture occupies intermediate values for b , when considering the total range of b values. On the other hand, for fixed values of a (or $1/a$, as depicted) it occupies low values of b (i.e. the Agriculture contour is located near the lower edge of the $-dQ/dt$ vs. Q data cloud). So indeed agricultural catchments have relatively low b values.

For forestry, the same reasoning can be reversed: although Swedish forests are intensively managed (ditches and remnants thereof are often present), the absence of annual soil cultivation can be expected to result in rehabilitation of natural soil profiles, where conductivity usually decreases with depth (Harr, 1977; Bonell, 1993; Bishop et al., 2004). An exponential conductivity profile is commonly assumed in many hillslope hydrological studies (Beven, 1997). Therefore, (re)forested catchments are expected to have values for b approaching their upper limit. Using the same line of reasoning, we note that the 80 % contour for Forest (Fig. 4) is characterized by intermediate values for b (in absolute terms) and low-to-intermediate values when considering typical values for a . However, observed trends all move towards higher b values, as expected.

It should be noted that above mechanisms focus on the upper ≈ 1 m, which is commonly unsaturated. Yet, this is the zone which is most relevant for stream flow recessions, because it represents the zone in between storm and inter-storm groundwater levels.

4.2 Functional interpretation of trends in recession parameters

A different view of the temporal trends in Brutsaert–Nieber parameters a and b is yielded by plotting trends in these parameters on top of the phase diagram as phase diagrams (Fig. 4b). As can be seen, most catchment migrate from smaller ($1/a$, b) towards larger ($1/a$, b). ~~This is interpreted as an~~ Given the similar pattern in the plots of (T , b ; Fig. 4c) and (T_0 , b ; Fig. 4d), we interpret these patterns as a general increase in transit time and nonlinearity of the recession process.

The observation that increasing exponent b is associated with increasing $1/a$ and hence decreasing a suggests that over time the power law Eq. (2), as converted to the linear law Eq. (7), rotates: the steeper the slope b , the lower the intercept $\log(a)$.

This hypothesis has been tested by plotting power laws for every 5 year period, and calculating the average point of rotation. It has been found that for the 35 “most complete” catchments in terms of data coverage the rotation point is predominantly (in 20 out of 35 cases) between the median and 75th percentile of $\log Q$. This suggest that recession has become slower (lower $-dQ/dt$) for lower discharge, and faster (higher $-dQ/dt$) for higher discharge), and that the former effect is stronger than the latter effect (see Fig. 5).

To put this on other words, during the last decades, under wet conditions, water is being drained at an increasing rate, while under dry conditions water is retained longer.

Two possible explanations are due to human impact on the landscape: water management and reforestation.

From the water management perspective, it is often a goal to level out extreme conditions. Too much water as well as too little water is considered harmful for many applications. This is especially true for agriculture: too much water is associated with flooding, intractable parcels of farm land and oxygen stress for crops. Too little water, on the other hand, is associated mainly with water stress for crops. An optimized agricultural water management is thus focused on enhanced draining during wet conditions (e.g. by artificial drainage) and enhanced retaining of water under (summer) dry conditions, e.g. by weirs.

As discussed below (Sect. 4.1.6), reforestation is expected to result in a rehabilitation of natural soil profiles, with hydraulic conductivity decreasing with depth. These type of conductivity profiles are associated with relatively high b values (Table 1). At the same time, intensive forestry is also associated with some form of artificial drainage (mainly ditches in Sweden) that have an effect on recession (decreasing a).

Indeed, many field studies have shown that, for the same soil type, forest have higher near-surface porosity and saturated conductivity (decreasing with depth), compared to pasture or degraded forest, where conductivity profiles are more uniform (Parker and Chartres, 1983; Bormann and Klaassen, 2008; Zimmermann and Elsenbeer, 2008), and that reforestation takes at least 10 years to restore conductivity profiles (Zimmermann et al., 2006; Zimmermann and Elsenbeer, 2008).

Summarizing, both intensification of water management and reforestation are argued to be consistent with the changes in recession parameters.

4.3 Similarity of recession analysis with efficiency analysis

It is interesting to compare the relative positions of the 80 % probability contours in our a vs. b diagram (Fig. 4) with a similar diagram plotting water efficiency E/P vs. energy efficiency E/E_{pot} , the ratio of actual to potential evapotranspiration (van der Velde et al., 2013a, their Fig. 7). For each combination of land use pairs the distance between the contours (as represented by their centroids) can be measured in both diagrams. When comparing these distances (Fig. 6) all but two pairs of distances line up nicely on a diagonal ($R^2 < 0.95$, when excluding the two outliers), suggesting that when the corresponding land cover types are similar in “recession space” they are also similar in “efficiency space”. Likewise, when land cover types are dissimilar in recession space, they are dissimilar in efficiency space. There are two exceptions. The combination Agriculture–Open Water is similar in energy efficiency-space, but dissimilar in recession space. For the combination Agriculture–Natural Open this is reversed.

Proximity (similarity) of Agriculture and Open Water in “efficiency space” can be understood from the fact that both are highly efficient with respect to water and energy. For Open Water, water limitation is virtually non-existent, and much of available energy is used for the evaporation process. For Agriculture, the high efficiencies can be understood from the intensive management and focus on optimal efficiency (i.e. making maximum use of resources). Meanwhile, the large distance (dissimilarity) between these two land cover types in “recession space” can be understood as well: Open Water is exactly that *because* it has a long recession time scale; if precipitation cannot be discharged quickly enough, storage increases until surface water bodies emerge. For agricultural areas it is the opposite: water availability is generally plenty, but energy and soil oxygen are potentially limiting factors, which both are improved by rapid (artificial) drainage.

The second combination of land cover types that deviate from the general pattern is that of Agriculture and Natural Open, which are proximal (similar) in recession space, but distal (dissimilar) in efficiency space. As explained by van der Velde et al. (2013a), the large distance in efficiency space is due to their almost complete opposite geographical conditions: Natural Open landscapes prevail high up in the mountains where temperatures are cold, while Agriculture is mainly located in the warmer lowlands. The proximity of these land cover types in recession types is perhaps more of a coincidence. Both types share a very similar fast recession (low $1/a$) but for different reasons: high up in the mountains slopes are steep and soils are young and shallow, both factors promoting fast drainage (Soulsby et al., 2006; Broxton et al., 2009; Tetzlaff et al., 2009), while, as argued before, fast drainage of agricultural areas is mainly due of artificial drainage.

5 Conclusions

About 50 years of daily streamflow data for 316 gauging stations in Sweden have been analysed in terms of Brutsaert and Nieber (1977) streamflow recession parameters, and trends therein. Some clear spatial patterns in recession parameters have been found: exponent b generally increases with latitude, causing a more linear ($b \approx 1$) streamflow response in the South, and a more nonlinear ($b > 1$) response in the North. Coefficient a , or rather the associated time scale $T = 1/a$, shows a reverse relationship, with slower drainage in the South, and faster drainage in the North. The spatial patterns of both $1/a$ and b are shown to be clearly linked to catchment properties from the climate-soil-landuse complex. Because of strong covariance of these different drivers, no dominant single driver could be identified.

Strong links with land cover have been identified. Each land cover class occupies a well-defined region within a - b phase-space, which can be linked to mechanistic explanations based on hydraulic and hydrologic process laws.

Moderate trends in both Brutsaert–Nieber parameters have been found. The general trend is towards slower (decreasing a) and more nonlinear (increasing b) recession. Although climatic factors are important to explain spatial patterns in recession parameters, trends in recession parameters are not statistically related to trends in either climate (mean annual temperature and/or precipitation) or streamflow magnitude (base flow, peak flow or average conditions), suggesting that recession parameters carry unique information, as shown earlier in the context of permafrost degradation (Sjöberg et al., 2012).

It is suggested that these trends in recession parameters are consistent with the dominant land use changes in Sweden during the second half of the 20th century, mainly reforestation combined with intensification of the remaining agricultural

areas. Both changes are expected to result in faster drainage under wet conditions and longer retention under dry conditions, leading to increased b and decreased a . Reasons for this transition differ though: for reforestation it is hypothesised to be due to a restoration of natural depth profiles of soil hydraulic properties, while for agricultural water management it is due to management associated with combinations of drainage (pipe drainage, ditches) and retention (weirs).

5 Many of the patterns and trends in recession parameters results could be attributed to various natural and anthropogenic drivers by invoking physics-based explanations. In other cases their independence to these drivers was confirmed.

Finally, relative positions of most land cover types in a - b “recession” phase space are strongly linked to relative positions in a similar “water and energy efficiency” phase-space plot (van der Velde et al., 2013a), strongly suggesting that land use, catchment-scale water retention characteristics and energy partitioning are strongly interrelated, and ~~possible~~possibly the
10 result of co-evolution of the landscape. Exceptions in this pattern could be well explained from both natural factors (slow drainage in open water dominated landscapes and cold conditions in mountainous natural open landscapes) and anthropogenic effects (yield optimizing crop and water management in agricultural areas).

One possible implication of these results is that models targeted at long-term prediction of stream flow dynamics should take into account the dynamical nature of catchment properties, especially the feedbacks associated with co-evolution of soils,
15 vegetation and land use.

Appendix A: Supplementary information

A1 Robustness of recession estimation methods

As explained in the main text, Stoelzle et al. (2013) compare three different recession extraction and parameterisation methods: BRU, after Brutsaert (2008), VOG, after Vogel and Kroll (1992), and KIR, after Kirchner (2009) and three associated parameterisation methods: Lower Envelop fitting (LE; Brutsaert, 2008), Linear Regression (REG; Vogel and Kroll, 1992), and Binning (BIN; Kirchner, 2009). All method combinations were tested, resulting in a total of 9 estimates of a and b (their Fig. 1).
20

For each extraction method, we computed and ranked the variability for the corresponding b estimates. A similar analysis for a would be strongly biased by values of b (because it is an intercept on log-log transformed recession data). Therefore, we use a new variable y , defined as $-dQ/dt$ for a characteristic reference Q (here 1 mm day^{-1}). Note that y has the same conceptual
25 meaning of a . Also, variability for the time scale parameter $T = 1/a$ has been analysed. A similar analysis has been performed for the three fitting models.

From these results (shown in Table 3), we conclude that the least variability in estimation of b , y and T is obtained from the VOG extraction method and the REG fitting method.

A2 Development of linear regression models

30 1. a Box-Cox power transformations was applied to each catchment characteristic, and to the river discharge recession parameters a and b , to improve normality of the data and importance of extremes in the dataset.

2. The transformed parameters a and b were each related to all combinations of the transformed catchment characteristics (from 1 ~~upto~~ up to 12 explaining variables) using multiple linear regression.
3. The optimal model was selected. This is the model with the lowest Bayesian Information Criterion (BIC). The BIC weights the number of explaining variables against the explained variance.
- 5 4. To reduce the sensitivity of the multiple linear regression to outliers in the dataset, the catchment that dominates the multiple linear regression in its absolute effect on the sum of explained variances (R^2) for both parameters a and b , was removed from the dataset. These first four steps were repeated until 5 % of the catchments that dominate the multiple linear regression were removed from the dataset.
- 10 5. An ensemble of 1000 unique multiple regression models was created by taking 1000 bootstrap samples of the remaining catchments and determining the optimal multiple regression model for each bootstrap sample via steps 1 to 3 of the above described procedure. The entire ensemble of 1000 multiple linear regression models was then used to represent the mean and uncertainty of parameters a and b .

A3 Recession exponent for weirs and open channel flow

For a broad-crested weir, $Q \propto LH^{3/2}$ (Henderson, 1966; Chaudhry, 2008), where L is the length of the weir, and H is the water depth above the weir. Assuming that effective storage S upstream of the weir is directly proportional to H , this results in $Q \propto S^{3/2}$. Using $b = 2 - 1/d$ (Eq. 3; Clark et al., 2009), we obtain $b = 4/3$.

Recession exponents for open channel flow are based on an analysis of stream channel networks. Within these networks, channel width W , depth D and velocity V are usually related to discharge Q by a power-law relation, the so-called hydraulic geometry relationships $W \propto Q^b$, $D \propto Q^f$ and $V \propto Q^m$. Because $Q = WDV$, $b + f + m = 1$. Locally, storage S can be expressed as $S \propto WD$ and therefore $S \propto Q^{b+f}$ implying $Q \propto S^{1/(b+f)}$. Again using $b = 2 - 1/d$ we obtain $b = 2 - (b + f)$.

In their classical paper introducing the topic, Leopold and Maddock Jr. (1953) distinguish between at-a-station and downstream hydraulic geometry. Analysing many rivers, they find $b = 0.26$, $f = 0.40$ and $m = 0.34$ (at-a-station) and $b = 0.5$, $f = 0.4$ and $m = 0.1$ (downstream), suggesting $b = 1.34$ and $b = 1.1$, respectively.

A detailed analysis of the New Zealand Ashley and Taieri river basins resulted in $b = 0.440$ and $f = 0.242$ (Ashley) and $b = 0.517$ and $f = 0.247$ (Taieri), suggesting Brutsaert–Nieber $b = 1.318$ and $b = 1.236$ (Ibbitt, 1997).

For Optimal Channel Networks (Rodríguez-Iturbe et al., 1992), $b = f = 0.5$, suggesting $b = 1$, but according to Molnar and Ramirez (2002) this is unlikely to occur in nature.

Above results are based on the assumption that only local storage $S = WD$ is related to discharge. A more landscape-scale approach can be obtained by taking total network storage into account.

30 As Howard (1990) has shown, optimal channel networks can also be created when random walk networks are combined with local drainage along steepest descent flow paths. For a virtual gridded stream network, generated with this technique, and scaled by total area of Ashley and Taieri basins, bankfull channel width and depth have been computed for each grid cell, using hydraulic geometry relations for these basins as described above. Now, for every grid cell, total channel storage upstream of

that grid cell can be computed and related to discharge (which is assumed to be proportional to drainage area). This resulted in $Q \propto S^{0.7875}$ (Ashley) and $Q \propto S^{0.7561}$ (Taieri) resulting in Brutsaert–Nieber $b = 0.73$ and $b = 0.68$, respectively.

To what extent Brutsaert–Nieber $b < 1$ are physically realistic remains to be seen. As Bogaart et al. (2013) have argued, any process that is unable to dry up completely within finite time (i.e. $Q \downarrow 0$ as $S \downarrow 0$) by necessity results in $b \geq 1$.

- 5 Summarizing, we conclude that open channel flow results in Brutsaert–Nieber exponents ranging from 1, when landscape-scale water storage is taken into account, to approximately 1.2–1.3 when only point-scale storage is taken into account.

A4 Metatrends

- For catchments where a significant trend has been found ($p < 0.05$), trend magnitude is related to parameter value (Fig. 7). For coefficient a , this relation is rather weak ($p = 0.047$), but for exponent b it is significant ($p = 0.0044$). This means that linear
10 (i.e. $b \approx 1$) catchments remained close to linear, but nonlinear catchment ($b > 1.5$) became more strongly nonlinear. It also clear from this figure that significant trends are mainly found for moderate parameter values. All trends for $b < 0.9$ or $b > 1.8$ were insignificant.

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Table 1. Analytical expressions for Brutsaert and Nieber (1977) recession parameters a and b , for various conditions. Here, k [L/T] is saturated hydraulic conductivity, f [-] is drainable porosity (specific yield), D [L] is active aquifer thickness (difference between initial phreatic surface and final drainage level), n is an exponent in the power-law conductivity model $k(z) = k_D(z/D)^n$ (Rupp and Selker, 2005). L [L] total length of the channel network, A [L^2] catchment area, such that L/A is drainage density, p [-] is a linearisation parameter (pD reflects a “representative” water table height), α [-] is slope angle, and B [L] is hillslope length. Note that B is associated with the inverse of drainage density L/A .

Model	Topography	Conductivity	a	b	Reference
Non-linear Bouss. ^a	Flat	Uniform	$1.133/kfD^3L^2$	3	Brutsaert and Nieber (1977)
Non-linear Bouss. ^b	Flat	Uniform	$4.8k^{1/2}L/fA^{3/2}$	1.5	Brutsaert and Nieber (1977)
Non-linear Bouss. ^b	Flat	Power-law	$\propto \frac{1}{f} \left[\frac{k_D L^2}{2^n (n+1) D^n A^{n+3}} \right]^{\frac{1}{n+2}}$	$\frac{2n+3}{n+2}$	Rupp and Selker (2005)
Non-linear Bouss. ^b	Sloping	Uniform		0	Bogaart et al. (2013)
Non-linear Bouss. ^b	Sloping	Power-law		$\frac{2n+1}{n+1}$	Rupp and Selker (2006b)
Linearized Bouss.	Flat	Uniform	$\pi^2 k p D L^2 / f A^2$	1	Brutsaert and Nieber (1977)
Linearized Bouss.	Sloping	Uniform	$2k(pD \cos^2 \alpha + B \sin \alpha) / f B^2$	1	Zecharias and Brutsaert (1988)
Kinematic wave	Sloping	Uniform		0	Bogaart et al. (2013)
Kinematic wave	Sloping	Exp. decr.		2	Troch et al. (1993)
Weir				1.33	Sect. A3
Channel flow				1–1.2	Sect. A3

^a“Early” time, i.e., right after sudden onset of drainage, when mainly the aquifer parts near the drainage channels contribute to baseflow.

^b“Late” time, i.e., when the whole aquifer contributes.

Table 2. Typical range in recession parameters for various dominant land use types for catchments of 100 km². Ranges are based on the envelopes of the 80 % probability region in Fig. 4.

Land use type	$1/a$	b
Agriculture	7–17	1.1–1.5
Wetland	9–22	1.5–1.9
Natural open	5–15	1.4–1.8
Forest	10–27	1.0–1.5
Open water	27–45	0.7–1.3

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Table 3. Analysis of variance of recession indicators with respect to three extraction methods and three fitting methods, using the results of (Stoelzle et al., 2013). Numbers between brackets denote ranks.

Extraction method	VOG	BRU	KIR
var(b)	0.272 (2nd)	0.327 (3th)	0.133 (1st)
var(y)	0.0202 (1st)	0.0236 (2nd)	0.0822 (3th)
var(T)	41.2 (1st)	43.4 (3th)	41.8 (2nd)
Overall rank	1st	3th	2nd
Fitting method	LE	REG	BIN
var(b)	0.254 (3th)	0.134 (1st)	0.164 (2nd)
var(y)	0.0009 (1st)	0.0119 (2nd)	0.0701 (3th)
var(T)	6.8 (3th)	4.3 (1st)	7.8 (2nd)
Overall rank	3th	1st	2nd

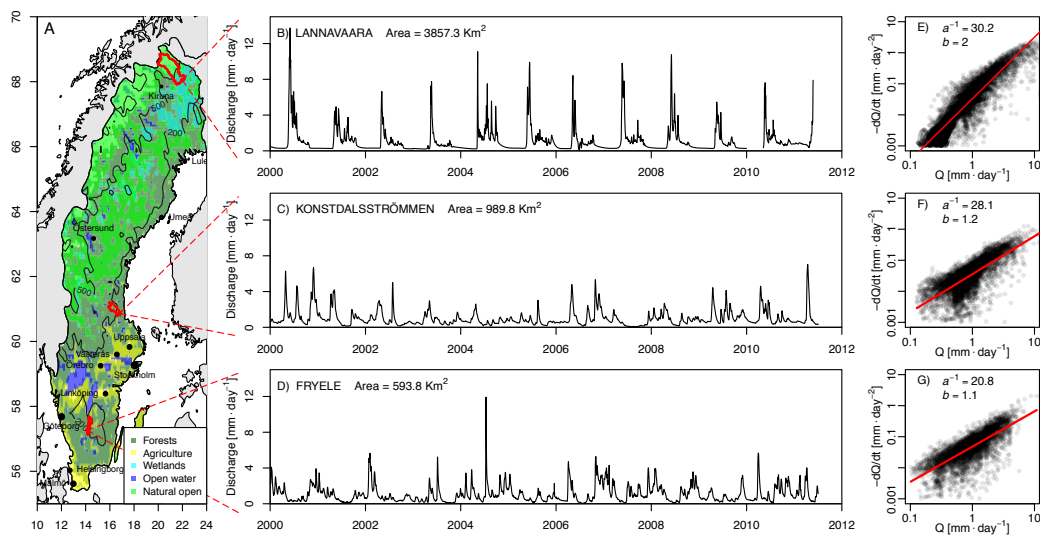


Figure 1. Land cover, elevation and major cities in Sweden, with three catchments highlighted. For each of these catchments the hydrographs (b, c and d) and the recession analyses (e, f and g) are shown.

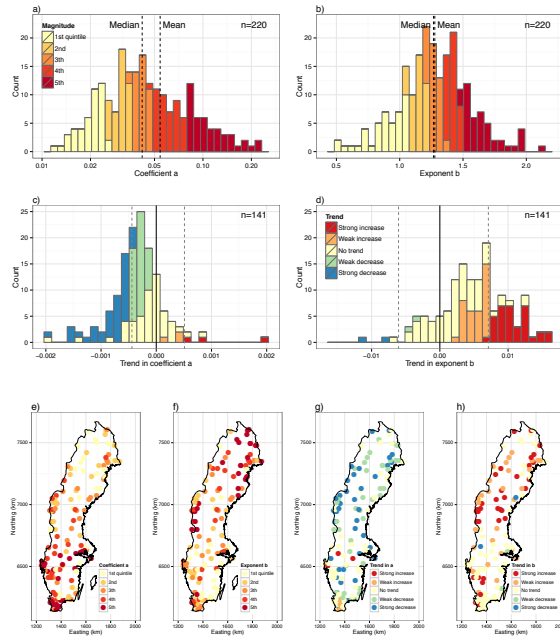


Figure 2. Top row: distributions of long term average catchment-scale Brutsaert–Nieber parameters a (**a**), note the log axis, and b (**b**). Coloured background panels indicate distribution quintiles, used as legends in (**e** and **f**). Centre row: trends in Brutsaert–Nieber parameters a and b (**c** and **d**, respectively) coloured by significance and magnitude class. Trends are identified as significant when $p < 0.1$. The threshold between strong and weak in- or decrease is taken to be the median of significant in- or decreasing trend magnitudes, and is indicated with dashed lines. Bottom row: absolute values (**e** and **f**) and trends (**g** and **h**) of Brutsaert–Nieber parameters a and b . Dots are coloured according to quintiles (absolute values, as in **a** and **b**), or significance class (trends, as in **c** and **d**).

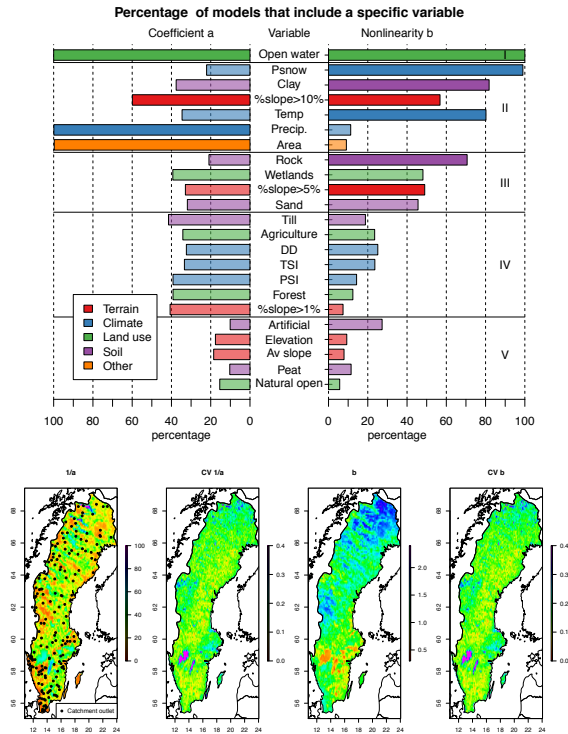


Figure 3. Top panel: explaining variables for Brutsaert–Nieber coefficient a (left) and exponent b (right), ordered by combined presence in regression models. Bars are coloured by category (Terrain, Climate, Soil, Land use, Other). Saturated bars indicate those variables that are required to approach maximum cumulative R^2 (≈ 0.8 for a and ≈ 0.7 for b). Bottom panels: spatial extrapolation of the Brutsaert–Nieber parameters, obtained by an ensemble of 1000 regression models and a uniform catchment area of 100 km^2 . Panels depict from left to right: (1) ensemble mean of $1/a$, (2) coefficient of variation of $1/a$, (3) ensemble mean of b , (4) coefficient of variation of b .

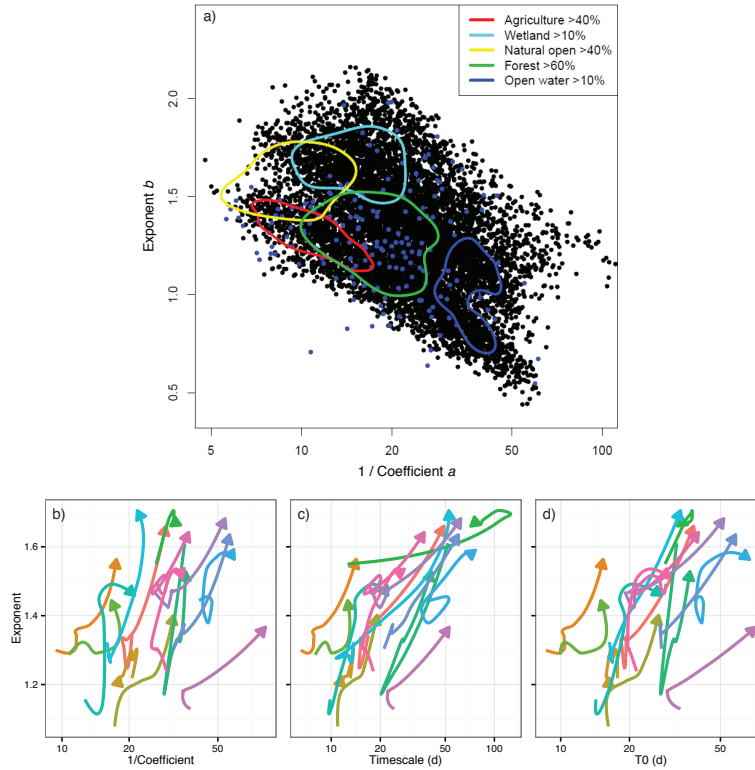


Figure 4. **a)** Landcover controls on Brutsaert–Nieber recession parameters a and b . The contours represent the 80 % probability region for 10 km gridcells with a dominant landcover. **Orange arrows indicate the direction of average trends for individual catchments.** Black dots represent the normalized 10 km grid cels; blue dots the original catchments. **b)** Trends in $1/a$ and b for the period 1950–2000, for a representative subset of catchments. Values are computed per catchment and year, using moving and overlapping 5-year time windows and smoothed in the time domain with a LOESS smoother. Colors identify individual catchments. **c)** Similar, but using the time scale T (Eq. (5), using the 95th percentile of Q as Q_0). **d)** Similar, but using the time scale T_0 (Eq. (6)).

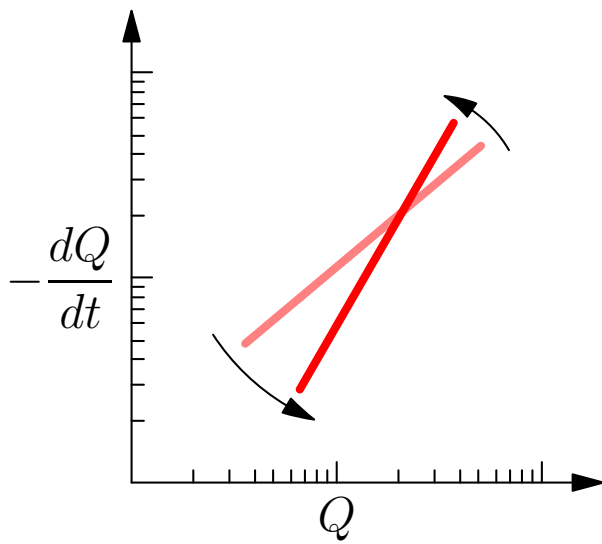


Figure 5. Conceptualization of the general trend in recession behaviour of Swedish catchments: a rotation of the powerlaw $-\frac{dQ}{dt} = aQ^b$ around intermediate $\log Q$ values.

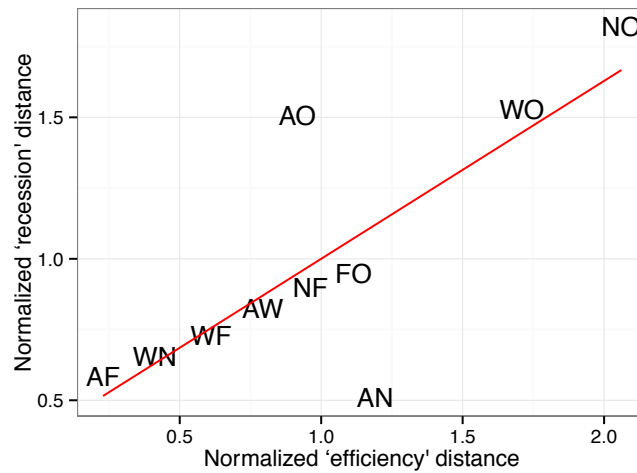


Figure 6. Normalized distance between centroids of 80% probability contours for land use, as depicted in Fig. 4 (“recession” distance’) vs. a similar distance for land use contours in the water efficiency/energy efficiency plot by van der Velde et al. (2013a) (their Fig. 7). Labels identify pairs of land use categories; abbreviations are: A = Agriculture; W = Wetland; N = Natural Open; F = Forest; O = Open Water. Distances are normalized such that the mean distance is 1.0 on each axis. The red line indicates a fitted linear regression model.

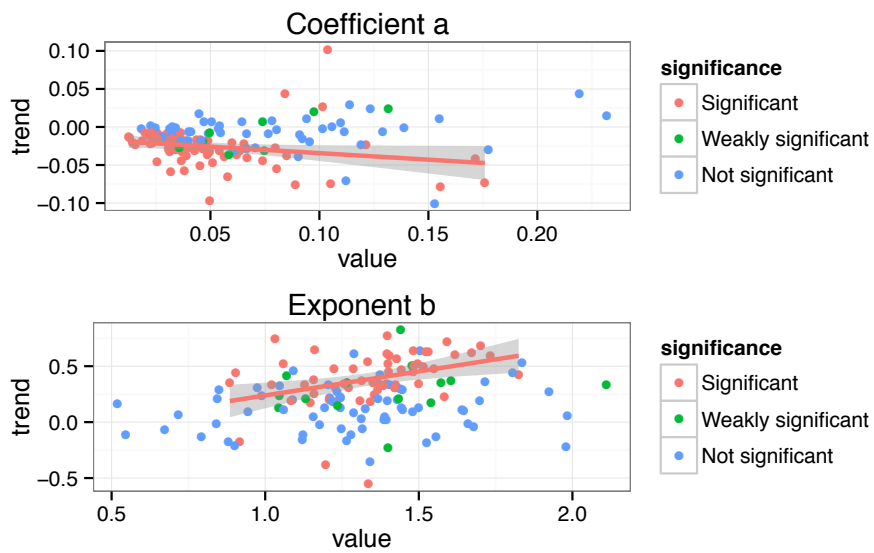


Figure 7. Dependence of trends in recession parameters a and b , related to static parameter values. Catchments are classified according to the p value of the trend analysis: significant for $p < 0.05$ and weakly significant for $0.05 < p < 0.1$. Also shown is a fitted linear regression model, along with the corresponding 95 % confidence bands (for significant catchments only).