Reply on Reviewer Comment #1

SUMMARY

This paper examines variability in streamflow recessions from and across 19 catchments in Taiwan. Recessions are characterized by the power-law recession parameters a and b in $-dQ/dt = aQ^b$. Differences in these parameters among recessions from a single catchment are compared to what are effectively antecedent moisture conditions using, as proxies, variables such precipitation amount and duration, discharge at the beginning of the recession, among others. Differences in parameters across catchments are compared to landscape properties, such as catchment area, shape, drainage density, stream length, among others. Parameter b, a measure of nonlinearity (where b = 1 indicates linearity) is found to increase with antecedent moisture in some basins but decrease in others. Large basins tend to show the former response, while smaller basins show the latter. In general, the smaller basins show the strongest relationship of b with landscape properties: e.g., b decreases with increasing drainage density in these basins. A hypothesis related to the degree of landscape heterogeneity in a basin is given for the contrasting responses between smaller and larger catchments, and two types of smaller catchments.

Reply:

We sincerely appreciate Reviewer #1’s comments. The reviewer is professional in recession analysis, fully understands our study, and points out the merits and weaknesses in the analysis as well. The main goal of this study attempts to clarify the recession responses to rainfall and landscape. Unlike previous studies which retrieved parameters from the synthesized point clouds or used the median of parameter distributions to discuss the effect of landscape on recession, we retrieved the *a* and *b* from individual event and thus the recession responses to different rainstorms under various landscape settings could be identified. Our results demonstrated that landscape heterogeneity (e.g. drainage area and L/G) in a basin regulates the direction of recession responses. All mentioned flaws in our estimation procedure and some unclear sentences were re-analyzed and rephrased. This reanalysis substantially improved the parameter estimation for the physical interpretation of the relationship between recession parameters on environmental factors. Although the value of recession parameters and correlation coefficients were updated, the contrasting recession responses do not change. The details of the re-analysis and point-to-point reply were described below.

GENERAL COMMENTS

The main contribution of this paper is the identification of different responses of recession shape (as characterized by b) to antecedent moisture and the apparent connection of these different responses to landscape properties. This is an important finding and may help explain contrasting results from other studies. Ultimately, I think this work could and should be published. However, the paper would require major revisions as there is one serious issue and a couple of weaknesses, which I describe below.

Reply:

As the reviewer recognized, the major finding of our work is that landscape properties modify different responses of recession shape to the initial moisture. This finding might have two important implications. One is that the landscape properties should be primarily examined (e.g. drainage area in our case) for determining the direction of recession response as assessing recession at a regional scale. Otherwise, the biased direction would lead to an controversial inference. Secondly, the influence of drainage area on contrasting recession responses needs further developments of a theoretical framework for physical interpretation.

The reviewer also pointed out one serious issue and a couple of weaknesses in our analysis. In this revision, we followed the reviewer's suggestions to improve our analysis procedure in order to make our results more concise and consistent with other studies. The details of the improvements were described below. All the comments are replied carefully and the unclear sentences were rephrased in order to elevate the scientific significance of our study.

1. The most serious issue in the paper is the faulty analysis of the parameter a. The fact is that no physical significance can be ascribed to changes in a when b also changes concurrently, therefore the paper's interpretation of the variability of a in this paper is flawed.

A problem arises from the units a, which change as b changes, as such the paper makes a nonsensical comparison of values of a with different units. One consequence of the scale dependence of a on b is that the reported differences in a among recession events is dependent, even in a relative sense, on the units the authors use for discharge Q. If this study were to use units other than mm hr-1, not only would the relative magnitudes of the differences change, so could the sign of the difference (while zero change is also possible given the correct units). If the reported differences in a had a physical significance, simply changing the units shouldn't change the physical interpretation. If in doubt, I suggest the authors redo some of their analysis after changing the units of streamflow from mm hr-1 to km hr-1 and nm hr-1 to see the effect.

This unit dependence of a on b is why, for example, Tashie et al. (2020b) and others fix b within a catchment and estimate a for each of the catchment's recessions. However, this does not solve the dilemma of comparing a across catchments where the catchments have different values of b.

I recommend the authors look to Dralle et al. (2015) and Biswal (2021) for further discussion on the relationship between the power law coefficients.

Reply: We are aware that parameter, *a*, is strongly affected by the unit and concurrently changes with b as fitting the power law equation to observations. In the original manuscript, we simply used runoff depth (mm, discharge normalized by drainage area to eliminate unit effect and keep the consistency among catchments). However, after the unit testing suggested by the reviewer, we found the relationships between *a* and *b* of our 260 cases are still unit dependent, strongly negative for nm, flat for cm, and strongly positive for both m and km for the unit of *a*. In this regard, using runoff depth (mm, the normalized discharge) is insufficient to eliminate the unit dependence between *a* and *b*, even though the relationships between *a* from different units and landscape indices remain unchanged. Therefore, we followed the reviewer's suggested references to re-analyze our cases.

Parameter dependency between *a* and *b* in recession analysis is inherent and entangled, which has no simple method to unravel. Biswal (2021) suggested to fix parameter *b* to obtain parameter *a* with the same unit for the interpretation of the variability. But, fixed *b* method cannot examine variation in *b* among rainstorms. In a different manner, Dralle et al. (2015) used the corrected (â, b) pairs to interpret the variation in *b*. This method scaled the original flow $\hat{Q}$ by a constant *k*, so the flow had a new value $Q = k\hat{Q}$. The power law relationship could be rewritten as: $-dQ/dt = ak^{b-1}\hat{Q}^{b}$. Therefore, the fitted $\hat{a}$ is equal to ak^{b-1}, showing the correlation of â and k^{b-1}. Decorrelating â and k^{b-1} can get a meaningful parameter *a* that is independent to *b*. Finally, rescaling $\hat{Q}$ by *a* value q_0 (ideally equal to $1/k$) leads to *a* free to *b* and $\hat{a} = a$. Since our study attempts to access both variation in *a* and *b*, the decorrelation method is appropriately applied to meaningful parameters, which is advantageous to compare *a* and *b* for different catchments. We added the decorrelation method in the revision for clarifying the calculation of corrected parameter estimation, in section 2.2.2 [Line: 169-173]: "*Secondly, varying units of â with b makes no physical meaning for comparison with other events or catchments. Since our target is to assess the response of dual parameters to rainfall, we used the decorrelation method (Drallet et al., 2015). This method assumes that the observed flow Q consists of a scale-free flow* $\hat{Q}$ *and a constant k* ($Q = k\hat{Q}$)*. Thus, the power law formula can be rewritten as* $-dQ/dt = ak^{b-1}\hat{Q}^{b}$*, where a is scale-free recession coefficient* [h^{-1}]*. For correcting â to a, the observed flow Q was divided by a constant* Q_0 *(ideally equal to 1/k, see details in Drallet et al., 2015).*"

The decorrelated a and b actually changed Fig. 2-Fig. 8, and Table 2. The correlation coefficients between landscape indices to a and b were updated. The corresponding changes, including text in Result and Discussion are also updated synchronously.

2. Although the authors reference various papers that have empirically examined the relationships between the power law recession parameters and environmental factors, very much has been published on these topics that is not referenced including relatively recent work (e.g., Tashie et al. 2020b). The paper should have a more comprehensive summary of prior work, followed by a clearer statement of what is still poorly understood, and finishing with what this study proposed to do to address one or more outstanding questions. While the intro does this to some extent, it is not sufficient.

A very valuable contribution would be, possibly in tabular form, a list of those environmental factors considered along with the studies that have found positive/negative/no relationship between these factors with recession parameters. This would clearly illustrate how much has been done and, hopefully, demonstrate why yet another study of this type is still necessary.

Note that while I have referenced numerous papers in this review, they do not include many empirical studies of recession parameters.

Reply: Thanks for this constructive suggestion. Accordingly, a substantial modification was made in the revised introduction. We collected additional 11 empirical and 5 theorical papers involved power law recessions since 2013 and tabulated the relationship between recession parameters and various environmental factors in Table 1 (24 empirical works of power law recession). From this table, most of the studies focused on the relationship between catchment centrality of parameters and environmental settings. Although recent works have examined the temporal variability of recession, their work majorly studied on a seasonal scale, or focused on parameter *a*. In other words, we found two important, but unsolved questions in our study. First, how do rainfall and physiographic variables affect recession parameters in different landscape regimes? So far, although several studies have explored the dependence of inter-event variably of recession parameters, their study sites located only in the USA. Thus, various responses among theories implying the control of landscape structure and rainfall amount on recession in different regions have room to be improved. Second, how does physiographic variables regulate the response of nonlinearity to rainfall? As we know, Biswal and Nagesh Kumar (2013) was the only work to find different responses of b to peak flow and interpret that the different responses are regulated by the subsurface storage gradient along a river. But what landscape variables control subsurface storage gradient is still unknown. We highlighted the two working hypotheses in paragraph 3 and 4 of the revised introduction [Line: 41- 59]:

> *"Theoretical works also illustrated the temporal dependence of recession parameters on the groundwater table, recharge, and storage. Parameter $\hat{a}$ has a negative correlation to the initial groundwater table (h_0) under unsaturated conditions and slightly positive under saturated conditions ($h_0 \geq B\tan\phi$, where B is the aquifer length and ϕ is the aquifer angle, Rupp and Selker, 2006). A large recharge rate also reduces parameter $\hat{a}$, particularly in homogenous catchments (Harman et al., 2009). On the other hand, hydraulic theories indicate that b decreases from 3.0 to 1.5 during the transition from early to late recession, as the groundwater is vertically sourced from different hydraulic properties in wet conditions (e.g., Rupp and Selker, 2006). The spatial heterogeneity theory demonstrates that the b only slightly increases with the wet antecedent condition (Harman et al., 2009). However, the drainage network theory indicates that b increases/decreases with storage while reaches in downstream are contributed by more/less subsurface storages (Biswal and Nagesh Kumar, 2013). The various responses among theories imply that the control of landscape structure and rainfall amount on recession in different regions should be explored further.*
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> *However, in empirical studies, we would argue that while there have been numerous empirical works of the power law recession analysis (summarized in Table 1 and S1), little understanding has been established in different regions and scarce interpretation on dual parameters of inter-event studies. First, USA studies account for nearly three-fourths of the prior works; even all studies of the inter-event variability were on sites in the USA (Table S1), which may ignore other different recession behaviors. For example, empirical recession parameters have inconsistent responses to several physiographic variables (drainage area, drainage density, water bodies coverage, and surface saturated conductivity), implying that different landscape regimes may have distinct recession responses. Secondly, most inter-event studies just analyzed the single parameter ($\hat{a}$) that decreases with the catchment wetness, which ignored the temporal variability of b. Only Biswal and Nagesh Kumar (2013) found that b may response to peak flow in different directions, but which landscape variables would control the direction is still unclear."*

3. The paper would greatly benefit from a discussion of what theory would predict for the influence of environmental factors on recession parameters. For examples, Figures 2 and 3 in Rupp and Selker (2006b) show how initial water table height (i.e., antecedent moisture), drainage density, hillslope slope and hillslope length/height ratio determine a and how vertical heterogeneity and initial conditions influence b. Are the results of this paper

consistent with theory? If not, why not? Perhaps theory breaks down outside of the idealized conditions upon which the theory is based? Theoretical work has also shown how planform shape and downstream boundary conditions (e.g., Troch et al. 2013) as well as a draining vadose zone (Luo et al., 2018) and drainage network geomorphology (Biswal and Marani 2010) can affect recession parameters.

Reply: Our original edition only took the spatial heterogeneity of flow velocity (Harman et al., 2009) to interpret the catchment variability of recession parameters. Indeed, including other theories could benefit the depth of discussion. In the hillslope hydraulic theory (Rupp and Selker, 2006), the shape of aquifer (length, depth, and gradient) can predict parameter a, which can be the analogy of our catchment-scale hillslope variables (flow-path length, height, gradient). The catchment-scale parameters (drainage area and total stream length) are the theorical predictor of a, but our results did not show the dependence. We suggest that the hillslope hydraulic theory can be used for interpreting the dependence of a on catchment-scale hillslope variables, but not for the actual catchment-scale variables. In the drainage network theory (Biswal and Marani 2010), parameter b can be predicted by the stream order law, but not for our cases.

Theories also show that rainfall/moisture among catchments would affect the responses of recession parameters. In hillslope hydraulics, the ratio of aquifer depth to groundwater table regulates the relationship between a and water table. While the initial water level is smaller than the aquifer depth, parameter a drastically decreases with the rising water table; while the water level is larger than the aquifer depth, parameter a is insensitive to the rising water table. Our results also showed this pattern. As for b, it is regulated by the vertical heterogeneity of hydraulic conductivity. Higher water table has more combinations of velocities in different storages, resulting in a larger b. In drainage network theory, the water table dominates extent of drainage network, controlling b increase or decrease with moisture. The different responses of b to rainfall are regulated by the subsurface storage contribution in each channel segment. Our empirical data showed that different responses of b to rainfall are related to the area, implying the area could be a proxy of subsurface storage change along the channel. The discussion has been updated as follows:

1. Section 4.2.1, Line [299-306]: "*Outlining among theories, flow-path variables could be regarded as the aggregation of aquifers with various geometries, or vertical heterogeneity of aquifer (Rupp and Selker, 2006). Flow-path variables L, H, G can be the proxy of* $B\cos\phi$*,* $B\sin\phi+D\cos\phi$*, and* $D/B+\tan\phi$*, respectively. Large* B *and* $\tan\phi$ *aquifers have a small coefficient a (Fig. 3 in Rupp and Selker, 2006). Catchments with long total stream length could have a large coefficient. While the flow-path has large H or G, its vertical heterogeneity of aquifer is probably high, also implying that a steep hillslope has a high n value (i.e., high vertical heterogeneity). Our inverse relationship between H and a confirms the theory (Rupp and Selker, 2006). Our catchment-scale flow-path variables could confirm the hillslope-scale aquifer geometry from the groundwater hydraulic theory.*"

2. Section 4.2.2, Line [318-322]: "*Theoretical b increases with aquifer heterogeneity (Rupp and Selker, 2006), inter-hillslope heterogeneity (Harman et al., 2009), and the number of stream (Biswal and Marani, 2010), yet decreases with the total stream length (Biswal and Marani, 2010). As mentioned before, steep catchments may*

lead to higher heterogeneity in aquifer and inter-hillslope, increasing the value of b. Also, the relationship between DD and b is consistent with the theories. However, these theories could not be valid in our large catchments, suggesting that prior theories were developed in hillslope or small catchment scale.”

3. Section 4.3.1, Line [346-351]: “*This phenomenon can be explained by Figure 12 in Rupp and Selker (2006). While the initial water table* h_0 *< aquifer length × gradient (*$B\tan\phi$*), parameter a is negative to the water table; when the initial water table >* $B\tan\phi$*, parameter a is insensitive to the water table. Three types of catchments follow a pattern that parameter a drastically decreases until approx. 250 mm and changes to constant. Interestingly, Type C has a higher intercept in the rainfall-a relationship like the theorical curve of h0/D=1, suggesting that the lower H of type C tends to be saturation and have a quick recession.*”
4. Section 4.3.2, Line [367-370]: “*Notably, the contrasting response of b to rainfall was only found in Biswal and Nagesh Kumar (2013) that attributed the change in subsurface flow contribution along the channel to the response direction of b. Our empirical data showed that drainage area regulates different responses of b to rainfall, implying the area could be a proxy of subsurface flow contribution to the channel.*”

LINE-BY-LINE COMMENTS

L1: The title could be improved. First, the meaning of the word “swing” in this context is unclear. A pendulum swings. I don’t think that is what the authors mean to say. Suggested replacements for “swing” are “modify” or “alter”. Second, “the response of recession nonlinearity” is also unclear.

Reply: Yes, the two terms, “swing” and “response of recession nonlinearity”, are unclear. We rephrased the title as: *Landscape structure regulates the contrasting responses of recession along rainfall amount*”. It clearly elucidated that the direction of recession response would be altered by landscape structure.

L12. Is it 260 sets of recession parameters per catchment, or in total over all 19 catchments?

Reply: Yes, it is the total number over all 19 catchments. We rephrased as: “*We derived a total of 291 pairs of recession coefficient, a, and nonlinearity, b, from power-law recession (-dQ/dt = aQb) over all 19 subtropical catchments with a broad rainfall spectrum.*” in Line 12.

L29-31: This sentence is out of place and not particularly relevant. The previous sentences are about analyzing individual recession events, while this is about projections of future rare rainfall events. Unless a stronger link is made, I would delete this sentence.

Reply: We removed this irrelevant sentence.

L32: Define Q and t in -dQ/dt = aQb .

Reply: Revised as: “*A power-law relationship between streamflow declines (streamflow rate Q recesses with a timestep t) with streamflow rates (-dQ/dt = âQb) can describe the recession characteristics at the catchment scale (Brutsaert and Nieber, 1977).*” in Line 31.

L34. I have an issue with calling a the recession rate. The units of a vary with b, so are not universally consistent with a "rate".

Reply: Yes, the unit of parameter a varies with flow and b, so "rate" is improper. We used *recession coefficient* in this revision. We checked this term and replaced recession rate with recession coefficient in the revision.

L38-41: It should be stated where discharge has been normalized by catchment area. From Figure 2, I take it that is has for the authors' analysis. The authors should be careful when discussing results from other studies that may not have normalized discharge. Brutsaert and Nieber (1977), for example, do not normalize discharge prior to comparing a from different basins with drainage density and network length but clearly dividing by area first would affect their values of a. Brutsaert and Nieber (1977) show an inverse relationship of a with total stream length (their Fig. 9) with seems to contradict the attribution to Bogaart et al. (2016) that a has a positive correlation with total stream length. Also, flow-path length and height need to be clearly defined.

Reply: Thanks for the reminder. In this revision, the discharge was normalized by drainage area and then used in the decorrelation method. The sentences, "*In this study, the stream discharge has been normalized by drainage area, and the unit of Q, $\hat{a}$ and b is [mm/h], $[h^{-1}(mm/h)^{1-b}]$ and [-], respectively.*", could be seen in Line: 115 to 116. Also, the comparison of a with other studies were carefully checked, seeing Table 1. The unit of a and discharge from each empirical study was marked. The recession responses to landscape indices were also indicated in Table 1. Thus, the consistency and contradiction from literature could be examined and discussed.

Finally, we defined L and H *and added the following sentences*, "*the flow-path is defined as the hillslope grid point following the surface flow direction toward the channel. Flow-path length (L) is the length of this path, and height (H) is the height difference along this path.*", in Line 89-91. We agree that unit of a may influence the response of a to environmental factors, other details are also important. In Brutsaert and Nieber (1977), the total stream length has a negative relation to a in the early part of recession and a positive relation in the late part of recession. As for Bogaart et al. (2016), they focused on the late part of recession and found a positive relationship between a and drainage density, which was not really contradict with Brutsaert and Nieber (1977). We put those into our discussion in this revision.

L42-43: Please cite the "few studies".

Reply: In this revision, we have included new references listed in Table 1. Event-scale studies account for one quarter of the previous works. Currently, "few studies" is no more a proper description. We replaced this sentence with the new one [Line: 59-60]: "*Only Biswal and Nagesh Kumar (2013) found that b may response to peak flow in different directions, but which landscape variables would control the direction is still unclear.*"

L46-47: I believe all the references except this one concern empirical studies, which makes this reference to theoretical work out of place. The statement is also unclear without more context. How does spatial heterogeneity affect whether increasing the steady-state recharge rate (I assume the authors mean a steady-state recharge rate immediately prior to the beginning of the recession) increases or reduces a? Maybe 1-2 paragraphs devoted to theoretical work could be included (see COMMENTS above).

Reply: Thanks to the reviewer, it's a good suggestion to include a paragraph focusing on theoretical work in introduction. We re-organized the introduction thoroughly. Now, the introduction has five paragraphs. The second paragraph described a basic background of recession parameters and their controlling factors from recession theories. The third paragraph elucidated the changes of recession parameters with catchment moisture from theoretical perspective. The fourth paragraph mainly described less contributions in prior empirical studies (with the new compiled table, Table 1). The new paragraphs read as follows [in Line: 30-59]:

> *"A power-law relationship between streamflow declines (streamflow rate Q recesses with a timestep t) with streamflow rates ($-dQ/dt = \hat{a}Q^b$) can describe the recession characteristics at the catchment scale (Brutsaert and Nieber, 1977). Parameter â is approximate to the recession rate but influenced by the unit of flow and b (see section 2.2.2), and parameter b represents the nonlinearity of storage. Recession parameters are often linked to the aquifer geometries, landscape, and spatial heterogeneity. Since the aquifer in various landscape units (e.g., hillslope, riparian, stream) exhibits different hydraulic properties, landscape structure, which presents the geometry of catchments and aggregates catchment hydraulic properties, apparently reflects various recession parameters. In theories, parameter â has a positive correlation with drainage density (total stream length/drainage area) and aquifer slopes but a negative correlation with aquifer depths, aquifer heterogeneity (of conductivity) (e.g., Brutsaert and Nieber, 1977; Rupp and Selker, 2006) and inter-hillslope heterogeneity (of celerity) (Harman et al., 2009). Parameter b increases with the number of streams (Biswal and Marani, 2010), the heterogeneity of the aquifer (Rupp and Selker, 2006) and the inter-hillslope (Harman et al., 2009), yet decrease with the total stream length (Biswal and Marani, 2010).*
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> *Theoretical works also illustrated the temporal dependence of recession parameters on the groundwater table, recharge, and storage. Parameter â has a negative correlation to the initial groundwater table (h_0) under unsaturated conditions and slightly positive under saturated conditions ($h_0 \geq B\tan\phi$, where B is aquifer length and ϕ is aquifer angle, Rupp and Selker, 2006). A large recharge rate also reduces parameter â, particularly in homogenous catchments (Harman et al., 2009). On the other hand, hydraulic theories indicated that b decreases from 3.0 to 1.5 during the transition from early and late recession, as the groundwater is vertically sourced from different hydraulic properties in wet conditions (e.g., Rupp and Selker, 2006). The spatial heterogeneity theory demonstrated that the b only slightly increases with the wet antecedent condition (Harman et al., 2009). However, the drainage network theory indicated that b increases/decreases with storage while reaches in downstream are contributed by more/less subsurface storages (Biswal and Nagesh Kumar, 2013). The various responses among theories implying the control of landscape structure and rainfall amount on recession in different regions should be improved.*
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> *However, in empirical studies, we would argue that while there have been numerous empirical works of the power law recession analysis (summarized in Table 1 and S1), little understanding has been established in different regions and scarce interpretation on dual parameters of inter-event studies. First, USA studies account for nearly three-fourths of the prior works; even all studies of the inter-event variability were on sites in the USA (Table S1), which may ignore other different recession behaviors. For example, empirical recession parameters have inconsistent responses to several physiographic variables (drainage area, drainage density, water bodies coverage, and surface saturated conductivity), implying that different landscape regimes may have distinct recession responses. Secondly, most inter-*

event studies just analyzed the single parameter (â) that decreases with the catchment wetness, which ignored the temporal variability of b. Only Biswal and Nagesh Kumar (2013) found that b may response to peak flow in different directions, but which landscape variables would control the direction is still unclear."

L50: Start new paragraph at "Due to…".

Reply: The paragraph was rephrased in [L64-67]: *"Due to frequent tropical cyclones (alias: typhoon) and mountainous landscapes, Taiwan's rivers generally have short water travel time and limit water retention capacity in catchments (Lee et al., 2020). Most typhoon rainwater falls in summer and elevates water level dramatically but diminishes quickly within 2-3 days (Huang et al., 2012)."*, and in [L72-74]: *"Understanding the recession behaviors after typhoons are vital to water resource management, particularly when global warming likely increases the frequency and magnitude of flood and drought (Shiu et al., 2012; Huang et al., 2014)."*

L76-77: Clearer definitions of L, H, and G are needed. Table S1 gives definitions in the footnotes, but they do not appear to be consistent with what is in the main text. The text says "flow-path length [L]" but Tables S1 says L is total length of the drainage networks. Are they the same thing? If so, the text on line 40 is confusing because total stream length and flow-path length are treated there as if they are distinct measures. The text also says "gradient (G) above the nearest channel" but the Table S1 footnote says "G is the average gradient of the drainage networks". These do not sound like the same thing.

Reply: Sorry for the unclear descriptions of the landscape characteristics. In this revision, we described all definitions in the main text and supplementary materials. The sentences of definitions are now added as "*Flow-path length (L) is the length of this flow-path (a flow strip from divide to stream), and flow-path height (H) is the height difference along this path. G is the flow-path gradient [-].*", in [L90-91]. The footnote of Table S2 was revised: "*Here, H is the flow-path height [L], L is the flow-path length [L], G is the flow-path gradient [-], A is the drainage area [L^2], DD is the drainage density [L/L^2], S_m is the gradient of mainstream, HI is the hypsometric integral [-], ELO is the basin elongation [-], CW, CF, CA is the land cover area of water, forest, and agriculture to total catchment area [-].*"

L86: Theissen polygons can be quite poor for interpolation of rainfall, particular in regions with sharp rainfall gradients such as in Taiwan. Is there additional information that can aid the interpolation, even a rainfall vs. elevation relationship? Are there any gridded climatologies (such as PRISM maps) that can be used to improve interpolation? What is the rain gauge density? Can the gauge locations be shown on a map?

Reply: We fully understand this issue and we had some experiences in the influence of spatial rainfall pattern to total flow and hydrograph (Huang et al., 2011, 2012). The grid-based rainfall (radar-based resolution ≅ 1.1 km) in Taiwan was available since 2002, while our events were derived from 1970s. Both the PRISM and the TRMM (resolution ≅ 5 km) also provided rainfall after 1990s, which do not meet the demand of this study. Due to the data limitation, only the rain gauges with sufficient historical records were used. In general, the rain gauge density in Taiwan is approximately 50 km^2 per gauge. Our previous studies showed that more dense gauges can describe the rainfall distribution, but the gauge requirement for total rainfall amount is relatively lower than for rainfall distribution

Huang, J.C., Kao, S.J., Lin, C.Y., Chang, P.L., Lee, T.Y., Li, M.H. (2011) Effect of subsampling tropical cyclone rainfall on flood hydrograph response in a subtropical mountainous catchment, *Journal of Hydrology*, 409 (1-2): 248-261, doi: 10.1016/j.jhydrol. 2011.08.037.

Huang, J.C., Yu, C.K., Lee, J.Y., Cheng, L.W., Lee, T.Y., Kao, S.J. (2012) Linking typhoon tracks and spatial rainfall patterns for improving flood lead time predictions over a mesoscale mountainous watershed, *Water Resources Research*, 48: W09540, doi:10.1029/2011WR011508.

L104-106: Dralle et al. (2017) could also be cited as an example of an examination of the effects of methodological choices.

Reply: We cited this work as suggested. This work examined the influence of the method choice to parameter estimation, which is very convincing and suitable to cite here. [Line: 125-127]: "*Dralle et al. (2017) also agreed with the above statement but they found that the relationship between â and antecedent wetness are sensitive to length of data.*".

L127-L131: How many recession events were ultimately included per station? Were they the same events in time per station?

Reply: For clarification, we added a sentence to the end of this paragraph: "*Ultimately, each watershed had 5 to 26 events selected for analysis (see Table S3), of which events were not necessarily the same*". [Line: 176-178]

L134: How exactly were dQ/dt and Q estimated from the data?

Reply: We thoroughly re-wrote the method section. Now, it is: "*Instead, the exponential time step method (Roques et al., 2017) was applied here to reduce the bias, in which the time step of the moving window exponentially increases along the recession. Each point within the moving window was used for the computation of the (Q, -dQ/t) pair; Q is the average discharge, and -dQ/dt is the slope of linear regression.*" [Line: 166-169]

L145-146: This sentence is confusing. First, please explain what it means that "the two parameters are interactively dependent". Second, why are they "particularly" dependent "when the number of points is huge". Lastly, what does this dependence have to do the ordinary least squares method?

Reply: In the original version, we have recognized the dependence between a and b and so we stated that the two parameters are interactively dependent. Besides, with the increase of points (high probability to include extreme events), the regression slope would be strongly biased by extreme events. In this revision, the section of material and method was thoroughly revised. The original sentence has been removed.

L152: Define elongation (ELO). How is it calculated? This should be explained in the methods section.

Reply: In this revision, all landscape characteristics were clearly described. Elongation, the ratio of the diameter of circle (same area with basin) to the basin length, can be expressed as $ELO = 2 (A/\pi)^{0.5}/L_B$. We added it in [Line: 88-89]: "*ELO is the basin elongation [-] defined as the ratio of the diameter of the circle (same area with the basin) to basin length.*"

L152-153: If the properties of W8 and W18 are described here, then so should they be for W5. How is W5 distinct from W8 and W18?

Reply: We took the low flow correction and decorrelation method into account and re-analyzed the dataset as the reviewer suggested. In this revision, we found that the L/G is more significant than other landscape indexes. Thus, the three samples became W9, W5, and W8. All three catchments were described [Line: 183-184]: "*Catchment W9 has a larger A and lower L/G, W5 has a lower A and lower L/G, and W8 has a smaller A and higher L/G.*"

L153-154: It is meaningless to rank in descending order of *a* if all the *a* do not have the same units. I suggest ranking them in order of *b*.
Reply: Ranking them in order of b in this revision [Line: 184-185]: "*In descending order, the ranking of median recession b is catchment W9, W5, and W8.*"

L154-155: Why are the mean and median of b stated for W8 but not for the others?
Reply: As replied before, in this revision, the recession parameters of the three catchments were all described [Line: 184-186]: "*In descending order, the ranking of median recession b is catchment W9 (2.34), W5 (1.96), and W8 (1.63). The point-cloud derived b are 1.45 (W9), 1.37(W5), and 0.88(W8), showing all point-cloud b are smaller than median ones (Fig. 2c).*"

L155-156: This sentence is confusing and I wonder if there is an error. Why would the median > mean of the recession rate (a) imply that the distribution of nonlinearity (b) is right-skewed? Fig 2c doesn't actually give the mean of a.
Reply: It was our mistake. Recession coefficient (*a*) should be the nonlinearity (*b*). But due to the mean recession *b* was not discussed later, we demonstrated the point-cloud b here [Line 185-186]: "*The point-cloud derived b are 1.45 (W9), 1.37(W5), and 0.88(W8), showing all point-cloud b are smaller than median ones (Fig. 2c).*". Additionally, we would state the median a and b and point-cloud b in Fig 2c.

L156-157: A plot of *b* vs storm magnitude and/or Q_{ini} for each of these three watersheds would be very helpful to illustrate the point being made, and show how strong these relationships actually are.
Reply: As suggested, we added plots of *b* vs Rainfall and inserted them into Figure 2c. It is a very useful and convincing suggestion. In the new inserted plot within Fig. 2c, it clearly showed the contrasting response of recession. Many thanks.

L157-158: I think the opposite response of W8 and W5 to storm magnitude being associated with differences in landscape properties should be left for the Discussion, but it is OK to foreshadow the discussion here. If this sentence is kept, I would follow it by saying that this apparent association will be explored further in the Discussion section.
Reply: Thanks for this suggestion. We added this suggested sentence, "*This apparent association will be explored further in the Discussion section*" in Line: 188.

L160: Units missing for a.
Reply: The unit of $\hat{a}$ is $[hr^{-1}\ (mm/hr)^{1-b}]$ and *a* is $[hr^{-1}]$. We added the unit here [Line 190]: "*Coefficient, a, ranges from 0.003 to 0.273 hr^{-1} with mean = 0.058 hr^{-1} and median = 0.047 hr^{-1}.*"

L167-170: Jachens et al. (2020) argue that this is not necessarily true; the point cloud fitting method may not reveal the "general" or average recession.
Reply: Yes, the term, "general", is not truly right. It just presents the bias description of

common recession [Line: 197-200].

L187: It should be noted here that P and Qini are effectively uncorrelated (r is only 0.11 and is not significantly different from zero). This seems like an important point and worth a little more discussion. How exactly is P calculated for each recession event? Over what time period is it totaled? This should be described in the methods.

Reply: We guess the reviewer may misunderstand Q_{ini} (the initial flow or antecedent flow of rainfall event) for the flow at the begin of recession (i.e., Q_p in our manuscript). Thus, we replaced Q_{ini} with Q_{ant} (antecedent flow). The rainfall period was defined as the elapse time from 6 hr before the rising flow to the peak flow. We described it in Methods [Line: 120-123].

L188: What are these "presumed thoughts". I would reiterate the thoughts here or leave this phrase out.

Reply: Re-think about it, we leave this phrase out.

L191: Describe how is L/G is a proxy for the interaction of landscape and climate. References?

Reply:

Rainfall-runoff is the main driver to shape the landscape and regulate landform evolution via erosion. Retrospectively, the geometry of landscape left by climate's watermark could identify the climate features (Seybold et al., 2017). In erosion, hillslope length and gradient are the key factors to erodibility, Therefore, L/G is a proxy for the interaction of landscape and climate. Moreover, McGuire et al. (2005) suggested that the flow path length and gradient distribution reflect the hydraulic driving force of catchment-scale transport (i.e. Darcy's law) and thus some description of topography (e.g. L, G, or L/G) provides a first-order control on flow processes and water residence time. We put some of the above descriptions in Line: 210-214.

Seybold, H., Rothman, D. H., & Kirchner, J. W. (2017). Climate's watermark in the geometry of stream networks. Geophysical Research Letters, 44(5), 2272-2280.

L214: Circular logic. The authors' definition of non-linearity is already that the value of b is not equal to 1. Also, values less than 1 are non-linear.

Reply: We believe that the reviewer's comments are about the sentence, "*Nonlinearity higher than 1.0 indicated….*", in the original manuscript, Line: 219. We rephrased it as, "*Non-linear storage-outflow relationship (b is not equal to 1.0) is prevalent for most catchments worldwide*". [Line: 234]

L220: It would be clearer to simply say highest and lowest values of b. Or "the most and least nonlinear cases are…".

Reply: As suggested, we used "*the highest and lowest median values of b*" instead. [Line: 250]

L230-232: But see also Sharma and Biswal (2022).

Reply: Thanks for suggesting this paper. This comment is similar to the previous one. We added a sentence, "*Notably, there is no single value of b preferable for all practical purposes.*" [Line: 260-262]

L238: "Complicates" is not a good term here. I think the authors mean to say that heterogeneity may increase with catchment area because of the possibility of including a wider range of subsurface conditions. This sentence should be rewritten for clarity.
Reply: We used the reviewer's sentence in Line: 267. Thanks.

L259: This is the first time any "Type" of catchment is mentioned. The classification of catchments into Types needs to be introduced more clearly. I would start a new paragraph and direct the reader to the upper half of Fig 9 (which will mean reordering the figures).
Reply: We reorganized the paragraph according this comment. Now, it is, "*According to Fig. 6b, all catchments could be simply classified into three types. Type A is large catchments (area > 500 km^2), B is small catchments with low L/G ratio, and C is small catchments with high L/G ratio.*" [Line: 291-293]

L271: I suggest rewriting as "The positive relationship of b with both H and L…."
Reply: Thanks for the rewording. The sentence has been rephrased as you wrote in Line 321-322: "*The positive relationship of b with H and L indicates that steeper and rougher hillslope present non-linear recession behavior.*"

L272: I don't understand this sentence. What are these "blocks"? How does higher H and L imply greater prevalence of such blocks?
Reply: Rephrased as, "*The positive relationship of b with H and L indicates that steeper and rougher hillslope present non-linear recession behavior. A possible interpretation is that with the increase of flow path, subsurface runoff has more chances flowing through various blocks (e.g. temporarily perched groundwater)*". [Line: 321-323]

L273-274: This is an important idea the authors introduce. Do only catchments with short AND gentle hillslopes have large riparian areas? How exactly does a larger riparian area reduce heterogeneity?
Reply: Rephrased as, "*Short-and-gentle hillslopes, which means their topographic wetness indices vary smoothly. The smooth distribution of topographic wetness indices would present the gentle expansion of saturation area during rainstorms from the perspective of TOPMODEL (Huang et al., 2009). The expansion of saturation area indicates the whole subsurface is getting saturated and connected and thus reduces heterogeneity.*" [Line: 323-324]

Huang, J.-C., Lee, T.-Y., and Kao, S.-J.: Simulating typhoon-induced storm hydrographs in subtropical mountainous watershed: an integrated 3-layer TOPMODEL, Hydrol. Earth Syst. Sci., 13, 27–40, https://doi.org/10.5194/hess-13-27-2009, 2009.

L276-277: Do these large basins have something in common other than being large? Almost all these large basins have their headwaters at the highest elevations and most of the smaller basin are on the west side. These smaller basins are also mostly in the rainshadow, whereas the larger basins receive much more rainfall. What role could these factors play?
Reply: Reviewer is right that most orographic, conventional, and frontal rainfall are strongly affected by landscape and form rainshadow. It's another interesting issue. But, our dataset with limited spatial resolution in rainfall can't support to test this hypothesis. Notably, typhoon, alias of tropical cyclone in Pacific Asia, has quick moving velocity with different trajectories. Moreover, it rotates counterclockwise quickly (depends on pressure gradient). In

this context, the rainshadow regions vary dynamically. We can't exclude the effect of rainfall distribution on recession raised by reviewer. This comment also likely interprets why the recession response to rainfall in large catchments are more non-linear. We put above descriptions into the revision [Section 4.3.2].

L279: "The large deviation" of what? Please be explicit.
Reply: Large deviation in the value of *a*. [Line: 338]

L303-314: I think it worth noting that *b* is treated as a constant here throughout a single recession event, though it has been empirically shown that it can change over the course of an event (e.g., Rupp and Selker 2006b; Tashie et al. 2020a). Also, groundwater hydraulic theory predicts that *b* can change over time (Brutseart and Nieber 1977). For a horizontal aquifer, this change depends on the initial conditions (Rupp and Selker 2006a) but the change in *b* happens relatively early and *b* becomes relatively steady as the recession progresses. In a sloping aquifer and/or one that is vertically compartmentalized, *b* can change over a lengthy part of the recession (e.g., Bogaart et al. 2013; Roques et al. 2022). How this theoretical idealized hillslope behavior might manifest in a complex catchment has still not been not well-described, however.
Reply: Yes, *b* might be time-variant during an event, since the saturation degree and hydraulic connectivity vary dynamically. We added that *b* is constant through a single recession event, in Line 378-379: "*Note that although b was found it can change over the course of an event* (Luo et al., 2018; Rupp and Selker 2006)*, this study treated b as a constant and the inter-event variability is discussed as the following.*"

L306: This is an interesting idea that the pervasive saturated overland flow reduces the nonlinearity of recession. Two issues: 1) What field evidence is there of this pervasive saturated area? 2) I expect this saturated area is decreasing in time, possible very quickly. How would this affect b? Thinking along the geomorphological lines of Biswal and Marani (2010), might this not increase b?
Reply:
The first issue has been replied in previous ones [L273-274] and [L326]. We don't have comprehensive field evidence, but do have some local experience. The second issue is also not easily replied. Yes, the saturated area decreases in time. But, our recession *b* was treated as a constant during an event; in other words, the saturated area that we indicated is at the beginning of recession (i.e., peak flow). Large saturated area, like more water bodies, would behave like a linear reservoir, resulting in a smaller *b*. Although the geomorphological lines of Biswal and Marani (2010) implied that *b* increase with the extent of drainage network (i.e., large rainfall), the uniform flow contributions along river are often not meet in real systems. Their revised model (Biswal and Nagesh Kumar, 2013) stated only large flow contribution in downstream could meet the positive relationship between *b* and peak flow.

L309-311: I'm not sure I follow this. How would a large rainstorm "connect" saturated zones of slow reservoirs that were otherwise not draining to a stream? What may be happening is that during large storms there is a wider range of active quickly to slowly draining sources (the fast ones being the ones activated during the large storms). This heterogeneity of sources can increase b. This appears to be what the authors say in the sentences following this one.

Reply: Thanks for making it more clearly. What we want to say is that with the connection of saturated zones, the large storms can activate different draining sources, mixing them downstream and result in the decrease of b (as Type C demonstrated). The above descriptions have been updated.

L326: Is there any field evidence for these perched storages?

Reply: Although there is no comprehensive observation on a larger scale, an experimental forested watershed in northern Taiwan was observed having perched subsurface water bodies (Liang, 2020). With the increasing rainfall, heterogenous subsurface saturations might be activated to contribute into the stream. We added a sentence: "*The existence of perched storages have been found in an experimental forested catchment in Taiwan by intensive pore water monitoring (Liang, 2020).*" [Line: 360]

Liang, W.-L. (2020). Hydrological responses in a natural forested headwater before and after subsurface displacement. Journal of Hydrology, 591: 125529. https://doi.org/10.1016/j.jhydrol.2020.125529.

L329: I wouldn't say "unpredictable". Predictability is not the issue here.

Reply: Eliminated.

L340: I would not say "pretty diverse". Is "inconsistent" what is meant?

Reply: As suggested, we replaced "*pretty diverse*" with "*inconsistent*" in Line: 370.

L346: What is meant by "higher hillslope hydraulics"?

Reply: Revised as "*higher L/G*". Other terms of hillslope hydraulics were also replaced with L/G.

Figure 2: The panels in column c clearer show discretization artifacts that visually hide the underlying relationship at low flows. A way to remove these artifacts was first proposed by Rupp and Selker (2006b) and modifications were made by Roques et al. (2017) and Guo et al. (2022). I suggest the authors apply one of these methods.

Reply: Thanks for this suggestion to discretize artifacts during low flow. For improving the estimations of recession parameters, in this revision, we applied the exponential time step method (Roques et al., 2017) to remove the discretization. We added the above descriptions in the section of material and method to clarify our estimation procedure [Line: 110-115].

Figure 5: State in caption whether all stations and all events are shown in this plot.

Reply: Now the sentence was phrased as, "*Recession parameter a and b from all catchment-events against landscape variables.*" in the caption of Fig. 5.

Figure 7: Say in caption which symbols are for Type A, B, and C, basin.

Reply: We added the descriptions of Type A, B, and C in Fig. 7. The sentence, "*Type A is large catchments (area > 500 km^2), B is small catchments with low L/G ratio, and C is small catchments with high L/G ratio.*" was added in the caption.

Table S1: Some of these basin average drainage network gradients are very large (as high as 0.75). Hillslope gradients must be yet larger. What are the implications for subsurface flow?

Table S1: L/G is given as having units of m2. If L has units of m and G is unitless, L/G must have units of m.

Reply: Sorry for the confusion. *G* is the flow-path gradient [-], not the average drainage network gradient. Therefore, the unit of *L/G* is [L]**.** We updated the definitions of *L* and *G* as, "L is the flow-path length [L], G is the flow-path gradient [-]" in the revised Table S1.