

Interactive comment on “Scaling properties reveal regulation of river flows in the Amazon through a “forest reservoir”” by Juan F. Salazar et al.

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Comment:

Editor Decision: Reconsider after major revisions (further review by Editor and Referees) (08 Sep 2017) by Patricia Saco

Comments to the Author:

Dear Authors,

We have received two detailed and insightful referee letters. After my own assessment of the manuscript and looking at the referee’s comments, I agree with both reviewers that the paper presents an interesting study of scaling characteristics of flow regulation, and an application to the classification of large Amazonian sub-catchments. I also agree that some aspects of the analysis need further analysis, particularly in the discussion, before consideration for publication.

Response:

Thank you. We gratefully acknowledge that yours and the reviewer’s comments have helped us to improve our manuscript. The main new elements of the revised version are the following:

- a) The Discussion section (Section 4) has been extended. It now includes three subsections about the use of LA as the scale parameter (Section 4.1); an extended discussion of the forest reservoir hypothesis (Section 4.2); and an extended discussion about the potential forest loss critical threshold (Section 4.3). Figure 6 is new, and former Figure 6 is now Figure 7.
- b) The Supplementary information has been extended to include results of the scaling analysis when using A (the traditional approach) as the scale parameter. We show that our main conclusions are consistent between both scaling models (using LA or A). These results are discussed in the main text. New elements include Figures S7 to S9 and Tables S9 to S15.

Comment:

The main points raised by the reviewers that need to be incorporated in a revised version of the manuscript are:

1) As mentioned by reviewer #1 Decreased water storage in the atmosphere, produces decreased precipitation (P is decreasing, so the sum of $ET+R$ is not constant). It is difficult to understand that runoff can increase, and this is the idea of why there could be a shift from a wet to a dry state at longer timescales as suggested in other studies of precipitation recycling. It is clear that runoff can increase as a result of decreased evapotranspiration, but perhaps you need to clearly identify differences in response times and consequences for short and long time scales. This is still unclear in your current responses to the referee's comments. It is also important to consider that, as mentioned by reviewer #1, moisture recycling has characteristic spatial scales. Please revise figure #6 and its interpretation accordingly. Therefore, though the link between reduced evapotranspiration and increased discharge is clear, the link to precipitation recycling is not. This has important implications for the discussion, as it emphasizes precipitation recycling.

Response:

Sections 4.2. and 4.3 now include an extended discussion of our forest reservoir (FR) hypothesis (we are now using "hypothesis" instead of "concept"). Here we summarize some important ideas, more details are given in the revised version.

We agree that P may change as a result of external forcings related to, e.g., climate change and variability. However, the FR hypothesis does not require P to be constant or independent of external forcings. New Figure 6 (which shows the FR control volume) and Equations 8 to 10 help to clarify this. The revised version includes the following clarifications:

- c) "P (precipitation), E (evapotranspiration) and I (infiltration) are not external fluxes but components of complex land-atmosphere interactions (e.g. precipitation recycling) that occur within the system and, therefore, are fundamental to the mechanisms that can explain the capacity of a basin system for regulating river flows. Although external forcings (e.g. climate change or variability effects) do affect the response of the system (R is not independent of Q), the capacity for regulating river flows can only be a consequence of the system's internal dynamics. Otherwise, if the response of a system simply follows external forcings (if R were entirely governed by Q), then there would be no capacity for regulation. Variations in the internal dynamics of water storage allow for the occurrence of different river flow regimes under the same external forcings." (par 13-9, i.e. paragraph in page 13-starting at line 9).
- d) Equations 8 to 10 show that, for any given external forcing (net atmospheric moisture convergence: Q) R can increase or decrease depending on how water storage changes within the system. The revised version includes the following: "The occurrence of floods or low flows is related, respectively, to the abundance or scarcity of water, which depend on external forcings that determine whether Q is large or small during any given time period (e.g. wet and dry seasons). Floods dampening depends on the capacity of the basin to retain water when Q is large (wet season), which implies increasing water storage, consistent with [Eq. 9]. Analogously, low flows amplification depends on the basin's capacity for releasing

previously-stored water when Q is small (dry season), therefore reducing water storage as described by [Eq. 10]" (par 13-21)

- e) "The importance of forests for the system's internal dynamics of water storage is highlighted by their relation with precipitation. Precipitation is not entirely determined by external forcings nor independent of the presence of forests. If precipitation regimes were independent of forest-related processes, then those regimes should not significantly change in response to forest cover change." (par 14-1)

We have extended the discussion about the effect of forests on river flows. Of note is that there is not a single, globally-applicable response to how river flows change as a result of forest cover change. The revised version includes the following clarifications:

- f) "Forest loss does not reduce or increase river flows in every basin at every temporal and spatial scale [References in the manuscript]. Fundamental reasons for this are that forests have an inherent capacity to either increase or decrease the water balance components, and that these effects have a complex and dynamic nature. For instance, forests can increase or decrease E via, respectively, opening or closing stomata, which is related to water availability: stomatal aperture tend to be increased during drought stress and decreased during excessive water stress [References in the manuscript]. Further, forest loss can significantly alter the hydraulic properties of soils, especially by reducing infiltrability [References in the manuscript]. Through these impacts, forest loss can alter all the water balance components in complex ways. If the effect of forest loss were always to reduce E (due to reduction of the cumulative leaf area) with no impact on P (as implicitly assumed in hydrological models that use P as a fixed input) nor on the hydraulic properties of soils and regulation capacity of the basin, then forest loss should be always associated with increased R and, therefore, increased floods and low flows. Likewise, if the effect of forest loss were always to increase E (related to, e.g. weaker stomatal regulation, disruption of below canopy shading and stability, and increased wind speed over the surface) with no other effects, then forest loss should always lead to reduced R and, therefore, reduced floods and low flows. In both cases, the effect of forest loss on extreme river flows would always be in the same direction. In contrast, the forest reservoir hypothesis considers that forest loss can have contrasting effects on low flows and floods, mainly because the production of these extreme flows is governed by different processes occurring during different seasons." (par 16-2)
- g) "[...] forests have a strong potential to enhance the capacity of river basins for storing water and controlling its release, as well as for producing contrasting and time-variable (e.g. seasonally different) effects on the water balance components. These dual and dynamic effects are key for regulation since it requires opposite effects on low flows (amplification) and floods (dampening)." (par 11-33)

We agree that P recycling is not a dominant processes at all spatial and temporal scales in every basin of the world. However, there is evidence that P recycling is a crucial process in the hydrological cycle of the Amazon and neighbouring basins. Using new Figure 6 and Fig.

7, we have extended the discussion about the role of P recycling in regulating river flows. The revised version includes the following clarifications:

- h) “Recycled precipitation (P_R) is a key factor for regulation because it represents a potentially large amount of water that can be retained within the system through land-atmosphere circulation (Fig. 6). Therefore, in largely forested basins, the precipitation recycling ratio is indicative of the importance for regulation of the forest-mediated land-atmosphere interactions. Global estimates indicate that land evaporation accounts for about half of continental precipitation [References in the manuscript], whereby forests are major contributors [References in the manuscript]. In the Amazon river basin, recycled precipitation also accounts for about half of the total precipitation [References in the manuscript].” (par 14-12)
- i) “Precipitation recycling is not a dominant process at all spatial and temporal scales in every basin of the world. It is difficult to quantify the degree to which terrestrial evapotranspiration supports the occurrence of precipitation within a certain region, partly because this mechanism has characteristic time and length scales, and depends on the size, shape and location of basins, as well as on the atmospheric pathways of moisture transport [References in the manuscript]. However, it is widely-recognized that precipitation recycling is a crucial process in the hydrological cycle of the Amazon and neighbouring basins [References in the manuscript]. All of the studied large basins are sinks (receive recycled precipitation) and sources (feed recycled precipitation through evapotranspiration) of significant amounts of continental moisture, with impacts that can be spread throughout the continent by complex cascading effects that are sensitive to forest cover change [References in the manuscript]. Global estimates indicate the length scale of precipitation recycling can be as low as 500 km in tropical regions [References in the manuscript], which is not excessively large compared with the size of the basins. The observed seasonal variability of atmospheric moisture pathways over South America allows for the occurrence of significant precipitation recycling all over the Amazon basin [References in the manuscript]. With this amount of forest-related precipitation, a disruption of the recycling mechanism has a strong potential to modify the internal dynamics of water transport and storage that control river flows regulation [References in the manuscript].” (par 15-3)

Figure 7 (this was Fig. 6 in the early version of the manuscript) is presented as a conceptual example of how forest loss can disrupt river flow regulation (increase the extremes amplitude) via weakening the forest reservoir. Using new Fig. 6 and Equations 8 to 10, we have included clarifications about the interpretation of Fig. 7. The revised version includes the following:

- j) “Forest loss does not weaken regulation because it changes the capacity of the atmospheric and terrestrial water storages, but mainly because it reduces the capacity of the basin system (Fig. 6) to retain water through its complex internal dynamics of land-atmosphere interactions. Figure 7 shows a conceptual example of how forest loss can disrupt river flow regulation (increase the extremes amplitude) via

weakening the forest reservoir. Forest loss can exacerbate floods by increasing R through reduction of E and I during the wet season when P is large due to large Q (Fig. 6 and Fig. 7a). E and I reduction can be associated, respectively, with reduced leaf area and infiltrability. E reduction can weaken P recycling as a mechanism for dampening floods by recirculating water within the system. These effects are consistent with an enhanced conversion of P into R during the wet season and, therefore, enhanced floods and reduced water storage. This is described by Eq. (9) where floods are not dampened if water storages (S_l+S_a) are not increased. Water storage reduction during the wet season results in a decreased capacity of the system to amplify low flows via base flow during the dry season (Fig. 7b). Amplifying low flows when Q is relatively small (the dry season) requires the release of water that has been previously stored, consistent with $d(S_l+S_a)/dt < 0$ in Eq. (10). Deforestation-induced reduction of P [References in the manuscript] or lengthening of the dry season [References in the manuscript], consistent with a disruption of the wet season onset [References in the manuscript], can further reduce low flows.” (par 16-32)

Comment:

2) As mentioned by Reviewer #2, and based on the results presented in your supplementary material, it is unclear what is the advantage of using LA instead of area for the scaling relations. Please explain and include this aspect in the discussion. At the moment, I don't see a clear discussion between differences, and the supplementary figures (that show the trends for A and LA, are not discussed). This is linked also to the last comment of this same reviewer that mentions that the role of LAI in the relationships proposed needs to be better explained. Please also consider including a discussion of the differences in results by accounting for LAI as opposed to using A ($S=A$ instead of $S=LA$).

Response:

Section 3 and Supplementary information now include results of the scaling analysis when using A as the scale parameter (the traditional approach). We show that the main results of our study are consistent among the two scaling models (using either LA or A). New elements that are included in the revised version are:

- k) Section 4.1: “The use of LA as scale parameter”
- l) Last Section of the Supplementary Information: “Scaling results using A as the scale parameter”. This Section includes new Figures S7 to S9 and Tables S9 to S15.
- m) Table 1 now includes results from both scaling models.

The main ideas that are discussed in Section 4.1. are the following:

- n) “Our general idea about the classification of river basins is independent of using LA as the scale parameter.” (par 10-3)
 - o) “The main results of our study are consistent among the two scaling models” (par 10-11)

 - p) “The use of A as the scale parameter relies on the idea that it represents the horizontal area over which precipitation falls. Using LA is conceptually consistent with this same idea, because LA describes the area through which evapotranspiration is transferred to the atmosphere.” (par 10-19)

 - q) “Using LA allows to explore the influence of a changing scale parameter. LA is much more sensitive to global change than A...” (par 10-27)
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Comment:

3) As mentioned by reviewer #2 the 60% threshold is not clear, as having just one “unregulated basin” is not enough to identify a threshold or transition. Note that the modified text, in the response to the comment, is still not addressing this issue.

Response:

We agree that there is not enough evidence to conclude that 60% forest cover is a critical threshold, and have clarified the conclusions accordingly. However, we maintain our conclusion about the existence of different regulation states and levels (e.g. Table 1) because it is based on the physical interpretation of the observed scaling properties, following the conceptual framework developed in Section 2. This conclusion neither requires that forests play an important role in regulation, nor ignores the potential role of other factors. The forest reservoir is a theoretical hypothesis (presented in Section 4.2.) which implies that the regulation capacity of a river basin can be importantly sensitive to forest cover change. From this perspective, we discuss, theoretically, how forest loss can cause a transition from the regulated to the unregulated state in a river basin, especially in the Amazon (Section 4.3.). The revised version includes the following:

- r) “Our conclusion that the Madeira and Tapajos are the less regulated basins, with Tapajos being unregulated (Table 1), relies only on the observed values of the scaling exponents, following the theoretical framework developed in Section 2. Therefore, this conclusion does not ignore the important role of geological and geomorphological processes [References in the manuscript]. Depending on the case study, different levels of regulation or transitions between states could be attributed to different causes. The forest reservoir hypothesis provides a potential explanation linking forest cover and river flow regulation. The idea is not that the effect of land cover (particularly forest cover in the Amazon) on river flows regulation is stronger than any other effect (e.g. geological and geomorphological effects), but that the role of land cover is not negligible and critically important because of its sensitivity to global change, especially in a region such as the Amazon where forest ecosystems are highly threatened and forest-related precipitation recycling plays a major role

[References in the manuscript]. We foresee a potential danger in the assumption that the regulation capacity of river basins depends on geomorphological and geological processes with land cover playing a negligible role. Under this assumption, land cover change (e.g. forest loss) would not change the capacity of river basins to regulate river flows.” (par 15-16)

- s) “The forest reservoir hypothesis implies that the regulation capacity of a river basin can be importantly sensitive to forest cover change. The size of artificial reservoirs determines their regulatory capacity. Likewise, the regulatory capacity of the forest reservoir depends on its size, which is related to the extent of forest cover. This implies that forest loss weakens regulation. The lower levels of regulation in the Madeira and Tapajos river basins (Table 1) are consistent with a weaker forest reservoir (these two basins are the less forested ones, Fig. 5a), likely related to extensive forest loss that has occurred along the arc-of-deforestation [References in the manuscript].” (par 16-19)
- t) “The identification of alternative regulation states from scaling properties in river basins (Section 2), together with the hypothesis that forest loss weakens the regulatory capacity, imply that forest loss can cause a transition from the regulated state to the unregulated state. This also implies that there is a forest cover critical threshold where the transition occurs. In our results, the forest cover fraction in the less regulated basins is ~ 0.60 , while in the more regulated basins it is > 0.70 (Fig. 5a), which suggest a possible range for the critical threshold. Although more-detailed studies are essential to understand regulation dynamics in different regions, as well as to identify potential critical thresholds, our analysis shows that scaling patterns may be used to characterize regulation states and infer transitions in river basins. Such empirical approaches are essential [References in the manuscript] because it is becoming clear that accurate mechanistic models to predict critical thresholds (or tipping points) are currently beyond our reach [References in the manuscript], and the detection of early-warning signals for critical transitions in complex systems (e.g. river basins) remains a fundamental challenge in environmental science today [References in the manuscript].” (par 18-10)
- u) “We have applied the proposed interpretation of river flows scaling properties to the Amazon river basin and found both the regulated (all except the Tapajos) and unregulated (the Tapajos) states among its main tributaries. Then we proposed the forest reservoir hypothesis to describe the natural capacity of river basins to regulate river flows through land-atmosphere interactions (mainly precipitation recycling) that depend strongly on the presence of forests, especially in the Amazon. A critical implication of this hypothesis is that forest loss can force the Amazonian river basins from regulated to unregulated states. This provides further evidence about the possible outcome of widespread forest loss in the Amazon, potentially involving forest loss critical thresholds, a matter of great uncertainty and concern [References in the manuscript].” (par 18-31)

Comment:

Please also consider addressing all the other comments by the reviewer's in the revised paper.

Response:

The revised version now considers the Editor's and Reviewers' comments, including:

- v) Reviewer 2 suggested to remove some dots from Fig. 3. We did not remove such points but clarified the interpretation. The Legend now includes the following: "Dots over the bars indicate whether the scaling exponent is significantly different to 1 ($p < 0.05$, the dot is not over 1) or not (the dot is over 1)."
- w) Figure 5 was modified after suggestion by Reviewer 2: forest cover now starts at 0.