Hydrology and
Earth System
Sciences
Discussions

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:

The authors propose a method to classify large rivers of Amazonia according to their capacity to attenuate low, mean and high flows. Then, they introduce the hypothesis of "forest reservoir" with the premise that land use and land cover changes can induce changes of the river regimes from regulated to unregulated states. The idea is interesting, and can provide new insights on the sensibility of river to land use changes, besides other well-known indexes such as river elasticity. However, I have various concerns about the manuscript and the proposed index, which need to be clarified and analyzed:

Response:

We thank the reviewer for his/her comments. Specific answers to each comment are provided below.

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Comment:

1) Regarding the idea of classification of large rivers based on a scaling property defined as the product of LAI and Drainage area, it should be noted that traditional approaches used in hydrology (for instance, Molinier et al. 1996 for the Amazon Basin) have shown that there are well-known relationships between discharge and drainage area. These relationships stands across scales simply because they are based on the continuity equation. Perhaps the new approach in the manuscript is to compare of regional indexes for low, mean and high flows. Having say so, in my opinion, there is no need to consider the LAI in the scaling parameters, once the drainage area explain most of the variability. In mathematical terms, LAI works like a constant value with no effect on the relationships, because LAI is fixed in each basin

Response:

We agree that the scaling relations between drainage area and river flows are well-known. Indeed, this is acknowledged in the Introduction (starting at line 17 of p.1). The main question that we are addressing is not whether the scaling relations are valid in the Amazon (this was expected), but how to interpret the values of scaling parameters in terms of physical processes. Despite important advances (e.g. Gupta and Dawdy, 1995), this remains an open scientific question, with important practical implications related to the prediction of hydrological consequences of global change.

The first aim of our paper is to provide a physical interpretation of the scaling properties (particularly the scaling exponents) that is novel (most previous studies have focused on the interpretation of the scaling exponents for floods only), and widely-applicable

to different basins worldwide (the only assumption is that river flows in a given river basin exhibit scaling properties through power laws of the form of equation (1)). This interpretation (presented in Section 2) does not require the use of the cumulative leaf area, LA, as the scale parameter. Instead, it allows to investigate the use of different scale parameters. This is why all of the equations in Section 2 (equations 1 through 6) use S as a general scale parameter that could be replaced, for instance, by A (the drainage area), LA, or other, depending on the case study.

Our general idea about the classification of river basins is not based on the use of LA as the scale parameter (LA is not used in Section 2). Scaling properties, represented by the values of the scaling exponents for mean and extreme river flows, provide a parsimonious description of river flow regime of any river basin and allow its classification as regulated or unregulated. LA was used as the scale parameter for the application of our general framework (presented in Section 2) to the particular case of the Amazon (presented in Section 3). However, we verified the consistency of our results when using A instead of LA as the scale parameter (Supplementary Figures S1 through S6 show the scaling relations using both A and LA for each basin). Our idea is not that LA should be used as the main scale parameter in any river basin, but that it can be successfully used as a scale parameter in the Amazon.

We consider that leaf area is a key biophysical attribute with a strong influence on the hydrological cycle in the Amazon. Evidence of this statement is that most climate models use leaf area as a parameter to describe the hydroclimatic consequences of land cover change in the Amazon. As stated in the paper: "Large scale forest degradation or loss is a major driver of environmental change in these river basins [References in the paper]. The capacity to maintain high evapotranspiration rates is a key attribute of Amazonian forests associated with their large cumulative area of leaves [References in the paper]. We take this into account by setting the [scale] parameter as S=LA..." (lines 9-13, p. 4).

Using LA instead of A as a scale parameter has practical implications for future stud-

ies. Using LA allows to explore the influence of a changing scale parameter. LA is much more sensitive to global change than A, in temporal scales that are relevant for decision-making. LA varies with time as a consequence of rapid ongoing global-change-related processes such as deforestation, forest die-off and forest degradation. Although studying this variability is out of the scope of our present study, we consider that our reported results provide basis for future studies.

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Comment:

2) In the paper of Molinier et al (1996), regional differences among the response between Amazon tributaries are explained in terms of the rainfall regime. Given the large size of the Amazon, the annual distribution of rainfall varies from northern to southern tributaries. In this context, it is not a surprise that the southern tributaries are generally less regulated than the northern tributaries, considering that the annual distribution of rainfall is relatively regular in northern Amazonia (due to the effect of the ITCZ), while in southern and eastern Amazonia seasonal variability is higher (related to the South American monsoon circulation).

Response:

We appreciate that the reviewer agrees with our result that Tapajos and Madeira (the southern tributaries) are the less regulated basins. This implies that our interpretation of the scaling properties (Section 2) of the Amazon and its main tributaries (Section 3) worked well on distinguishing the more and less regulated basins.

The precise meaning of the comment about the seasonal variability of rainfall is not entirely clear to us. The intra-annual variability of rainfall is very pronounced all across the Amazon (e.g. Fig. 5 of Espinoza et al., 2009; and Fig. 2 of Molinier et al., 1996). We have assumed that the reviewer refers to the amplitude of the annual cycle of precipitation, which tends to be higher in the south. More or less amplitude of the rainfall seasonal cycle do not necessarily imply greater or lower capacity of a basin to regulate

river flows. For instance, Tapajos and Madeira are both located in the south, but their scaling properties indicate that they are significantly different in terms of regulation. While Madeira is regulated (mainly due to its capacity to dampen floods), Tapajos is unregulated (mainly because it dampens low flows). If the capacity of the Tapajos basin system to store water and control its release were big enough, then the basin would behave as regulated despite its seasonal rainfall regime. Our idea is that such capacity is importantly (not exclusively) dependent on the biophysical processes related to land cover, especially forest cover. Notably, the most regulated basin (Solimoes) is not a northern tributary, its drainage area ranges from southern to northern Amazonia. Further, the northernmost basin (Negro), is not the most regulated either. In our response to the fourth comment we include a conceptual example considering whether the regulation capacity of a basin could change due to forest loss, even without changing the rainfall regime.

The capacity of a system to regulate its response must be an internal property of the system rather than a consequence of external forcings. Seasonality is essentially a result of external forcings related to climatic effects of solar radiation variations. The capacity to regulate implies the capacity of a system to modify its response via its internal dynamics. If the response simply follows external forcings, then there is no capacity for regulation. The system that we are considering in our hypothesis of the forest reservoir concept "considers a river basin as the coupled land-atmosphere system comprising not only the terrestrial fluxes and storages of water but also the atmospheric ones" (lines 29-31, p. 10). Therefore, precipitation is not an external flux but an internal one, and the land-atmosphere interactions (e.g. those involved in precipitation recycling) occur within the system. Our idea is that these interactions are part of the mechanisms that explain the capacity of the system to store water and control its release (release outside the system through river flows), i.e. the capacity for regulating river flows.

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Comment:

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3) Besides the effects of rainfall regimes across the Amazon, the Basin can be divided in contrasting morpho-structural units (Molinier et al 1996). The implication of this is relevant in terms of the ability of the basin to accumulate water in the groundwater system and, consequently, in the capacity of Amazon tributaries for attenuating floods and droughts. This has been explore in detail by Miguez-Macho and Fan (2012), who showed that headwater responses are dominated by the effect of groundwater,while on large floodplains there are a two-way fluxes between surficial water and groundwater. This is why in several areas, such along the Solimoes and Amazonas, the degree of regulation is higher: those areas are characterized by large floodplains in combination with powerful aquifer systems (the Solimoes and Alter-do-Chao Formations). In other words, damping effects on the river main stem are the result of geological and geomorphological processes.

Response:

Following on our response to the first comment, the first aim of our paper is not to explain the causes of river flow regulation but to show how river flow regulation can be assessed from scaling properties (Section 2). This interpretation of the scaling properties does not ignore the role of geological and geomorphological processes. The scaling properties are based on river flow observations that are the result of all of the biophysical processes playing a role in the hydrological cycle. Therefore, depending on the case study, different levels of regulation (identified through scaling properties) might be attributed to different causes. As stated in the paper: "The physical causes for a river basin to be regulated or unregulated are summarized by its capacity for storing water and controlling its release. [...] River basins have natural mechanisms to implement these processes of water handling. These mechanisms depend not only on relatively invariant physical attributes (e.g. geomorphological and geological properties), but also on biophysical processes and characteristics of river basins that can be highly sensitive to global change at policy-relevant time scales, such as forest cover in the Amazon [References in the paper]." (lines 16-21, p.10).

We agree that geomorphological and geological processes affect the capacity of basins to regulate river flows. However, we also propose that the role of forests (particularly in the Amazon) in determining the regulation capacity of a river basin cannot be neglected. This discussion has important practical implications. As stated in the paper: "Identifying those factors that are both highly sensitive to global change and strongly influential on runoff production is crucial for predicting the potential effects of global change on river flow regimes. Vegetation cover and vegetation-related processes meet these two conditions in many river basins of the world [References in the paper], and particularly in the Amazon where the role of forests is so relevant that forest loss could force the system beyond a tipping point [References in the paper]". From this perspective, the regulation capacity of a river basin may be more sensitive to land cover change-related processes. In synthesis, the regulation capacity of a river basin could be mostly dependent on land cover-independent geological and geomorphological attributes (relatively invariant), while importantly sensitive to land cover (highly dynamic).

We consider that the paper by Miguez-Macho and Fan (2012), a very good modelling study, does not allow to produce a "definite" explanation about how and why the regulation capacity of river basins in the Amazon differs between one another. This is mainly because of the limitations of the coarse modelling study that the same authors acknowledge. As stated by the authors: "Despite [their] best effort, the model cannot escape from several fundamental deficiencies. One difficulty is with regard to the application of the one-dimensional Richard's equation with fine layers over large model grids of horizontal homogeneity. [Their] grid size of 2 km cannot differentiate hillslopes from first-order stream valleys, a fundamental scale of water movement on and near the land surface. This topographic gradient from hilltops to valleys also underlies many observed systematic changes in soil and vegetation. Resolving fluxes at this scale over continental regions is crucial but yet infeasible. A second but related difficulty is the use of coarsely gridded global soil maps such as the FAO product, obtained from agricultural surveys of topsoils ($\sim$1 m), for calculating water fluxes in very fine layers. [...] A third (and related to the second) difficulty is the complete lack of information on

the hydro-stratigraphy of the subsurface. Groundwater movement is controlled by the permeability structure of sediments and fractured rocks. Despite a century of aquifer characterization in many parts of the world, there remains a complete lack of basic data sets beyond the single-slope or single-aquifer scale, such as the depth to the bedrock and the vertical structures of porosity and permeability. Large-scale land models must rely on assumptions such as exponential decay of permeability with depth, which is widely adopted but at the same time widely known to grossly misrepresent the real-world." (Miguez-Macho and Fan, 2012).

The aim of our proposed hypothesis of the forest reservoir is not to produce a definite explanation of the causes for a river basin to be regulated or unregulated. Instead, our aim is to present a sound scientific hypothesis that may be further tested and discussed. Miguez-Macho and Fan (2012) concluded that "[the limitations of their study] can only be addressed collectively and in time. The saving grace is that the land surface topography has an enormous power in driving the movement of water at and near the surface. As shown [...], by simply allowing the gravity-driven flow in the subsurface, and letting the water level difference to determine the groundwater-surface water exchange, one can gain important, albeit qualitative, insights on the likely hydrologic states and fluxes near the land surface." In the same spirit, we consider that the difficulties in explaining the regulation capacity of river basins and its potential dependence on forest cover can only be addressed collectively and in time. The results and hypothesis presented in our paper are intended to be a contribution in this direction.

We foresee a potential danger in the assumption that the regulation capacity of river basins depends on geomorphological and geological processes with land cover (forest cover in the Amazon) playing a negligible role. Under this assumption, land cover change (e.g. vegetation change implying forest loss) would not change the capacity of river basins to regulate river flows. This is in contrast with many studies that show important land cover change effects on river flow regimes [References in the paper].

Our idea is not that the role of land cover (particularly forest in the Amazon) in river

flows regulation is more or less relevant than the role of geological and geomorphological processes, but that the role of land cover is not negligible, especially in the context of rapid global change. We agree that geological and geomorphological processes are first order drivers of basin's hydrological functioning (lines 15-25 p. 10). However, we want to emphasize that there is a fundamental difference between geological and geomorphological attributes and land cover-related biophysical properties. This difference relates to their sensitivity to global change.

In our response to the following comment we include a conceptual example to consider the idea that the regulatory capacity of a river basin is mostly controlled by geological and geomorphological processes, with land cover change-related processes being negligible. This will further develop our answer to this comment.

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Comment:

4) Finally, the authors suggest a series of change due to the effect of land use and land cover changes on the ability of rivers to regulate the response. Although this is a conceptually sound hypothesis, demonstration based on river data observations, rather than modeling, have proven to be quite illusive in large basins. For instance, detailed analysis of trends on rivers (Marengo, 2009; Espinoza et al. 2009) showed that the trends detected are associated to interdecadal variability, instead of the potential effects of land use changes. Moreover, recent trends in the hydrological cycle of the Amazon have also been attributed to the warming of the Atlantic Ocean (Gloor et al. 2015) rather than local-scale changes. If we take into consideration that most of the ability to regulate river regimes is related to rainfall regimes and geological – geomorphological characteristics ,as demonstrated before, it might be challenging to disentangle LUCC effects from those major natural drivers.

Response:

To clarify our response to this and other comments, we propose the following concep-

tual example: compare the regulation capacity of two land cover scenarios for the same basin. In the first scenario the basin is predominantly covered by forests (the "Forested basin"). In the second scenario all the forests are lost (the "Deforested basin"). The only difference between scenarios is land cover. All other attributes of the basin, including geological and geomorphological properties that are independent of land cover, are the same in both scenarios. We assume that the rainfall regime is also the same in both scenarios (below we will revise this, because precipitation and land/forest cover are not independent). The question is whether the Forested and Deforested basins have the same capacity for regulating river flows. The answer would be yes, only if the effects of deforestation on river flows were negligible. Many observational and modelling studies have shown significant effects of deforestation on river flows [References in the paper], even under the assumption of precipitation invariance (this is assumed when modelling land cover scenarios with hydrological models that use precipitation as an input, but does not allow for vegetation feedbacks on precipitation).

The idea in our paper is that the regulation capacity would be significatively different between the Forested and Deforested basins, even if they had the same rainfall regime. Typical effects of tropical deforestation include reduction of surface permeability and infiltration capacity (due to, for instance, loss of deep and complex root systems, reduction of surface roughness associated with vegetation structural complexity, and increase of rainfall compaction effect), and increase of direct runoff (associated to a smoother, less permeable surface). A reduction of surface permeability and infiltration is consistent with reduced base flow and, therefore, reduced low flows. Similarly, an increase of direct runoff is consistent with increased floods. This exacerbation of extreme flows is consistent with a basin that has a lower capacity to store water (e.g. via infiltration) and to control its release (e.g. via base flow or direct runoff). Collectively, these effects are consistent with a basin (the Deforested basin) that has a lower (as compared to the Forested basin) capacity for dampening floods and amplifying low flows, i.e. a less regulated basin.

Regarding the potential influence of climate variability on regulation, it is important to recall our response to the second comment. In particular, that the regulation capacity of a basin system is a consequence of its internal dynamics rather than a result of the influence of external forcings. Our proposed hypothesis considers precipitation as a flux within the coupled-land atmosphere system of a river basin. We consider that precipitation is not independent of forest cover, especially in the Amazon. Many studies have shown that forest loss can alter precipitation regimes over the Amazon.

Our study does not aim to isolate the role of land cover (forests) from all other factors affecting river flows regulation. Our hypothesis of the forest reservoir is intended to describe mechanisms through which forests can exert an important influence on the capacity of river basins to regulate river flows. Advancing towards this understanding of the relation between forest cover and river flows regulation is crucial for water management- and land cover-related decisions.

Comment:

In conclusion, it is my opinion that the manuscript should go through a major revision. The authors need to explain better the role of LAI in the relationships they proposed (which I think is unnecessary). Regarding the forest reservoir hypothesis, the concept should be clearer if an example based on observations is brought into the manuscript. I presume that, along the "deforestation arc", several candidate basins undergoing through severe land use and land cover changes in the last decades can be found.

Response:

We are positive that we have successfully addressed the reviewer's concerns and are willing to provide further explanation if required. We appreciate the reviewers's suggestion about studying individual basins along the deforestation arc. However, this would not be feasible, as our proposed approach (based on scaling) requires multiple scale observations, such as those that we have already included in the analysis.

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