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Discussions

Scaling properties reveal regulation of river flows in the Amazon through a "forest reservoir"

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Abstract. Many natural and social phenomena depend on river flow regimes that are being altered by global change. Understanding the mechanisms behind such alterations is crucial for predicting river flow regimes in a changing environment. Here we introduce a novel physical interpretation of the scaling properties of river flows, and show that it leads to a parsimonious characterization of the flow regime of any river basin. This allows to classify river basins as regulated or unregulated, and to identify a critical threshold between these states. We applied this framework to the Amazon river basin and found both states among its main tributaries. Then we introduce the "forest reservoir" concept to explain how forest loss can force the Amazonian river basins from regulated to unregulated states. Our results provide theoretical and applied foundations for predicting hydrological impacts of global change, including the detection of early-warning signals for critical transitions in river basins.

1 Introduction

Mean and extreme river flows are global-change-sensitive components of river flow regimes that are determinant for many ecological and societal processes (Sterling et al., 2013; Piao et al., 2007; Coe et al., 2009; Mahe et al., 2005; Lima et al., 2014; Zhang et al., 2016). Landscape and climate alterations foreshadow shifts of precipitation and river flow regimes (Botter et al., 2013; Boers et al., 2017; Hirota et al., 2011; Davidson et al., 2012; Khanna et al., 2017; Lawrence and Vandecar, 2015; Zemp et al., 2017; Sampaio et al., 2007). The conversion of precipitation into river flow through the accumulation of runoff depends on a suite of complex and heterogeneous biophysical processes and attributes of river basins, at different scales (Blöschl et al., 2007; McDonnell et al., 2007). This conversion results in spatial scaling properties —properties that do not vary within a wide range of scales— observable through river flow records (Gupta et al., 2007; Gupta and Waymire, 1990). The existence of scaling properties in river basins implies power law correlation between the system response —river flows— and a scale parameter —typically the drainage area—(Gupta et al., 2007). Power laws go beyond statistical fitting, they indicate scale-invariance as a fundamental feature of many systems in nature (Sivapalan, 2005; Brown et al., 2002; Kéfi et al., 2007). Scaling properties are common to river basins with very different environmental conditions (Poveda et al., 2007; Gupta et al., 2010).

This suggests that the spatial scaling properties of river flows have a common, mechanistic origin, that has been related to conservation principles and the fractal nature of river networks (Gupta et al., 2007; Sivapalan, 2005).

The values of the scaling parameters —the scaling exponent and coefficient of a given power law— are neither universal nor static features of river basins, because they depend on runoff production processes that are spatially heterogeneous (McDonnell et al., 2007; Blöschl et al., 2007) and sensitive to both climate and land cover change (Sterling et al., 2013; Piao et al., 2007; Mahe et al., 2005; Coe et al., 2009). Understanding the mechanisms behind the scaling parameters in river basins, as well as their sensitivity to global change, is a crucial step for enabling the use of the scaling theory in hydrological *prediction in ungaged basins* (the "PUB problem" (Hrachowitz et al., 2013)) and, more generally, in a changing environment where the processes governing the hydrological cycle are not static (the "Panta Rhei—Everything Flows" debate (Montanari et al., 2013)). We address this problem by linking the scaling properties of river flows to the capacity of river basins for regulating their hydrological response.

2 Scaling Properties Reveal River Flow Regulation

The scaling properties of river flows are evidenced through power laws of the form (Gupta and Waymire, 1990)

$$E[Q_i^k] = \alpha_i S^{\beta_i}, \tag{1}$$

where $E[Q_i^k]$ is the kth order statistical moment of the probability distribution function of river flows, S is a scale parameter, and α_i and β_i are the scaling coefficient and exponent, respectively. Q_i can be floods $(i = F)$, mean flows $(i = M)$ or low flows $(i = L)$. The scaling parameters (α_i and β_i) vary among river basins and flow types, and are always positive because river flows cannot be negative and increase downstream as a consequence of mass continuity.

The state of a river basin can be classified as *regulated* or *unregulated* depending on its river flow regime, which determines how the scaling exponents for floods (β_F), mean flows (β_M) and low flows (β_L) are organized. Regulation is defined here as the capacity of river basins to attenuate the amplitude of the river flow regime, that is to reduce the difference between floods and low flows. A river basin is regulated if $\beta_L > \beta_M > \beta_F$ or unregulated if $\beta_L < \beta_M < \beta_F$. A metric of the extremes amplitude is the difference (Δ_Q) between long-term average floods ($E[Q_F]$) and low flows ($E[Q_L]$), relative to mean flows ($E[Q_M]$),

$$\Delta_Q = \frac{E[Q_F] - E[Q_L]}{E[Q_M]} = \frac{\alpha_F S^{\beta_F} - \alpha_L S^{\beta_L}}{\alpha_M S^{\beta_M}}. \tag{2}$$

Our distinction between regulated and unregulated states is consistent with the definition of regulation in artificial reservoirs, whereby a reservoir regulates river flows by either mitigating floods through water retention or enhancing low flows through water release (Magilligan and Nislow, 2005). The extremes amplitude is dampened in the regulated state (Δ_Q is reduced as S increases), or amplified in the unregulated state (Δ_Q is increased as S increases), as a consequence of how river flows grow downstream in a river basin. These contrasting behaviours are reflected by the scaling exponents through the spatial rate of change

$$\frac{\partial \Delta_Q}{\partial S} = \frac{\alpha_F S^{\beta_F}(\beta_F - \beta_M) + \alpha_L S^{\beta_L}(\beta_M - \beta_L)}{\alpha_M S^{\beta_M + 1}} \begin{cases} < 0, & \text{if } \beta_L > \beta_M > \beta_F \text{ (regulated state)} \\ = 0, & \text{if } \beta_L = \beta_M = \beta_F \text{ (critical threshold)} \\ > 0, & \text{if } \beta_L < \beta_M < \beta_F \text{ (unregulated state).} \end{cases} \tag{3}$$

The difference between the regulated and unregulated states is evidenced by the theoretical limit

$$\lim_{S \to \infty} \Delta_Q = \begin{cases} 0, & \text{if } \beta_L > \beta_M > \beta_F \text{ (regulated state)} \\ (\alpha_F - \alpha_L)/\alpha_M \text{ (a positive constant)}, & \text{if } \beta_L = \beta_M = \beta_F \text{ (critical threshold)} \\ \infty, & \text{if } \beta_L < \beta_M < \beta_F \text{ (unregulated state).} \end{cases} \tag{4}$$

In the regulated state, the flow regime tends to the limit of complete regulation (constant flow: $E[Q_F] = E[Q_M] = E[Q_L]$), owing to the capacity of the river basin to dampen extremes ($\Delta_Q \to 0$). The opposite occurs in the unregulated state: the extremes are amplified ($\Delta_Q \to \infty$) and, hence, $E[Q_F] >> E[Q_M] >> E[Q_L]$. Therefore, in a given river basin, reversing the direction of the inequality from $\beta_L > \beta_M > \beta_F$ to $\beta_L < \beta_M < \beta_F$ indicates a shift between the regulated and unregulated states, with $\beta_L = \beta_M = \beta_F$ being a critical threshold. This agrees with the definition of a tipping point as "*the corresponding critical point —in forcing and a feature of the system— at which the future state of the system is qualitatively altered*" (Lenton, 2011). The difference $(\beta_L - \beta_F)$ is a metric of the regulation level that indicates the proximity to the critical threshold in a river basin. Everything else being equal, a reduction of β_L indicates an increased severity of low flows, whereas an increase of β_F indicates an increase of flood severity.

The occurrence of regulated or unregulated states depends on the combined effect of *dampening* and *amplification* processes operating within a river basin. Both processes can coexist in a regulated river basin because higher regulation implies both reducing floods through a dampening effect produced by water retention within the basin, and increasing low flows through an amplification effect resulting from the release of water stored within the basin. The occurrence of one or another of these effects is described by how the rate of change

$$\frac{\partial E[Q_i^k]}{\partial S} = \alpha_i \beta_i S^{\beta_i - 1} \tag{5}$$

grows with increasing scale. If $\partial E[Q_i^k]/dS$ decreases with S —power law (1) is convex in S—, then the flows are dampened within the river basin, meaning that the production of runoff per unit area decreases downstream along the river network.

The opposite occurs if $\partial E[Q_i^k]/dS$ increases with S —power law (1) is concave in S—. Whether $\partial E[Q_i^k]/dS$ increases or decreases with increasing S is determined by the value of the scaling exponent β_i relative to 1, as given by

$$\frac{\partial^2 E[Q_i^k]}{\partial S^2} = \alpha_i \beta_i (\beta_i - 1) S^{\beta_i - 2} \begin{cases} < 0, & \text{if } 0 < \beta_i < 1 \text{ (dampening process)} \\ = 0, & \text{if } \beta_i = 1 \text{ (critical point)} \\ > 0, & \text{if } \beta_i > 1 \text{ (amplification process),} \end{cases} \tag{6}$$

whereby $0 < \beta_i < 1$ and $\beta_i > 1$ represent, respectively, the dampening and amplification processes, and $\beta_i = 1$ is a critical value around which the curvature of power law (1) —and therefore the sign of its second derivative— changes. Higher regulation leads to dampened floods ($0 < \beta_F < 1$) and enhanced low flows ($\beta_L > 1$).

3 Regulated and Unregulated Basins in the Amazon

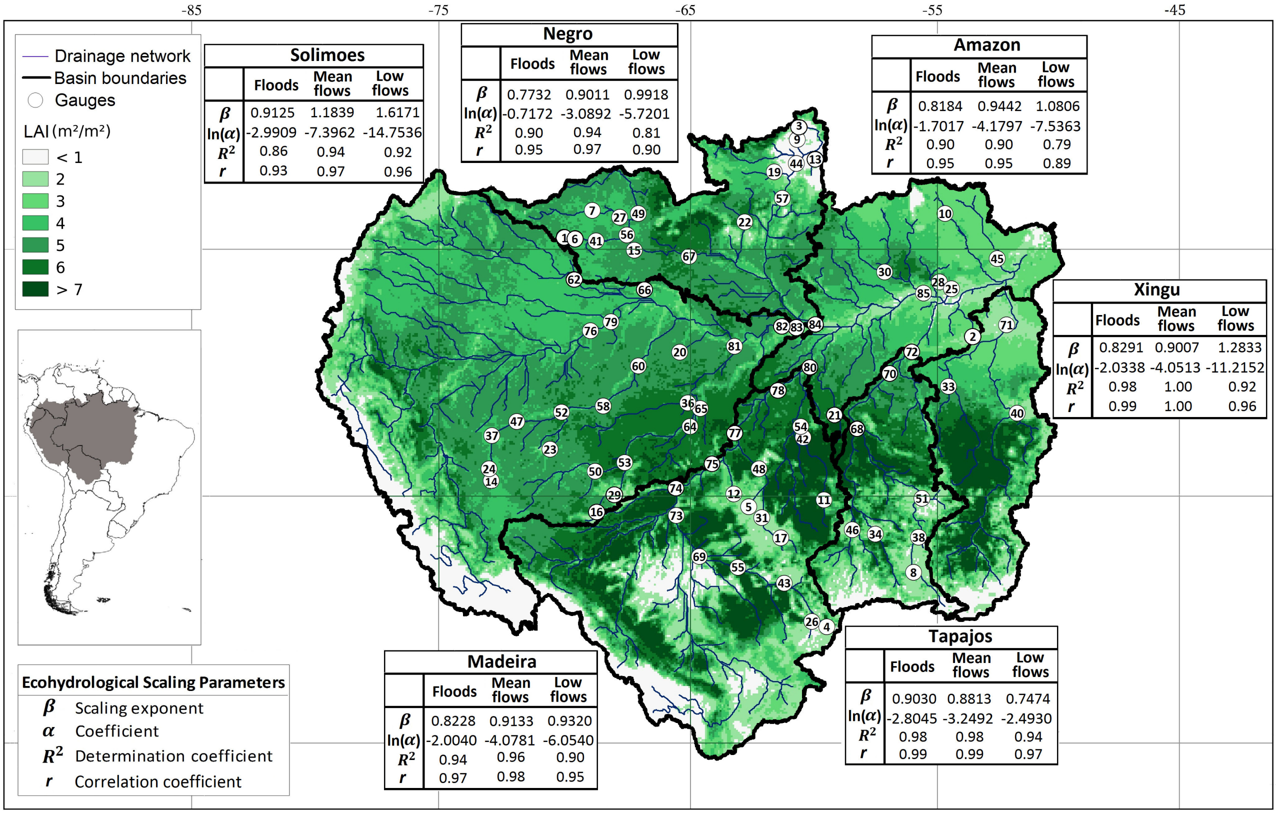
We tested our physical interpretation of the scaling properties in the Amazon river basin as a whole, and in its major sub-basins treated as independent systems (Fig. 1). Large scale forest degradation or loss is a major driver of environmental change in these river basins (Lawrence and Vandecar, 2015; Boers et al., 2017; Hirota et al., 2011; Davidson et al., 2012; Khanna et al., 2017; Zemp et al., 2017; Coe et al., 2009; Lima et al., 2014). The capacity to maintain high evapotranspiration rates is a key attribute of Amazonian forests associated with their large cumulative area of leaves (Da Rocha et al., 2009; von Randow et al., 2012; Caldararu et al., 2012). We take this into account by setting the scaling parameter as $S = LA = A \times \overline{LAI}$, where $\overline{LAI}$ is the leaf area index averaged over the drainage area A of each basin, so power law (1) becomes

$$E[Q_i^k] = \alpha_i LA^{\beta_i}. \tag{7}$$

Using basin topographic data and daily river flow records from 85 gauges from the SO-HYBAM project (Cochonneau et al., 2006) (Fig. 1 and Supplementary Table S1), and LAI data (Liu et al., 2012) averaged for 1981–2012 (Fig. 1), we found that annual mean and extreme river flows ($E[Q_i^k]$ with $k = 1$) in the Amazonian basins exhibit significant ($p < 0.05$, t-test results are in Supplementary Table S2) scaling properties through power laws of the form (7) (Fig. 2).

Current values of the scaling exponents reveal the existence of both regulated and unregulated basins within the Amazon (Fig. 3). The Amazon, Negro, Solimoes and Madeira river basins are regulated as indicated by their scaling exponents: $\beta_L > \beta_M > \beta_F$ —statistical significance of the comparisons between the scaling exponents in the Xingu river is limited because of the few degrees of freedom determined by the number of gauges, so we excluded this basin from this analysis—. In these regulated basins, Δ_Q decreases with the spatial scale, as given by (3) and (4) with $\beta_L > \beta_M > \beta_F$ (Fig. 4). In contrast, the scaling exponents ($\beta_L < \beta_M < \beta_F$) indicate that the Tapajos river basin has already transitioned into the unregulated state, whereby Δ_Q is not reduced with the spatial scale.

River basins can be classified by their regulation level: $\beta_L - \beta_F$ (Table 1). The Solimoes is the more regulated basin ($\beta_L - \beta_F = 0.70 > 0$), while the Madeira is still regulated but close to the critical threshold ($\beta_L - \beta_F = 0.11 > 0$) and the Tapajos



Solimoes

	Floods	Mean flows	Low flows
β	0.9125	1.1839	1.6171
$\ln(\alpha)$	-2.9909	-7.3962	-14.7536
R^2	0.86	0.94	0.92
r	0.93	0.97	0.96

Negro

	Floods	Mean flows	Low flows
β	0.7732	0.9011	0.9918
$\ln(\alpha)$	-0.7172	-3.0892	-5.7201
R^2	0.90	0.94	0.81
r	0.95	0.97	0.90

Amazon

	Floods	Mean flows	Low flows
β	0.8184	0.9442	1.0806
$\ln(\alpha)$	-1.7017	-4.1797	-7.5363
R^2	0.90	0.90	0.79
r	0.95	0.95	0.89

Xingu

	Floods	Mean flows	Low flows
β	0.8291	0.9007	1.2833
$\ln(\alpha)$	-2.0338	-4.0513	-11.2152
R^2	0.98	1.00	0.92
r	0.99	1.00	0.96

Madeira

	Floods	Mean flows	Low flows
β	0.8228	0.9133	0.9320
$\ln(\alpha)$	-2.0040	-4.0781	-6.0540
R^2	0.94	0.96	0.90
r	0.97	0.98	0.95

Tapajos

	Floods	Mean flows	Low flows
β	0.9030	0.8813	0.7474
$\ln(\alpha)$	-2.8045	-3.2492	-2.4930
R^2	0.98	0.98	0.94
r	0.99	0.99	0.97

Figure 1. The Amazon basin and its major sub-basins. The map shows the long-term leaf area index averaged over the period 1981–2012, boundaries and drainage network of the sub-basins, and river flow gauges provided by the SO-HYBAM project (www.ore-hybam.org). Detailed information about the gauges is in Supplementary Table S1. Tables show the parameters of power laws for mean and extreme river flows in each basin (details are given below).

basin has already transitioned to the unregulated state ($\beta_L - \beta_F = -0.16 < 0$). The Amazon as a whole is in the regulated state, but it is less regulated than the Solimoes ($\beta_L - \beta_F = 0.26$). In the following section, we explore the physical mechanisms behind the occurrence of different regulation states.

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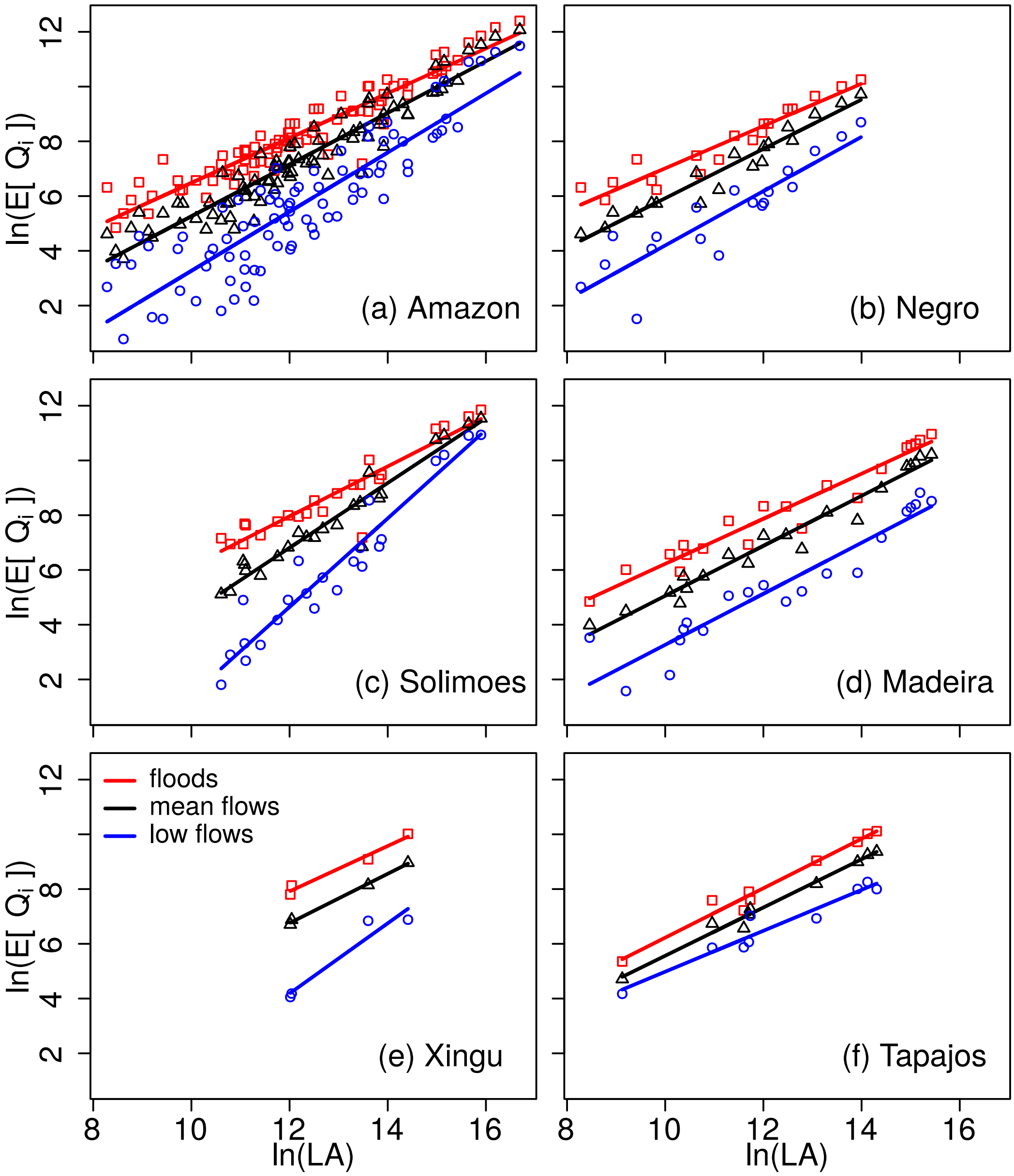

Figure 2. Power laws of the form $E[Q_i] = \alpha_i LA^{\beta_i}$ (Eq. 7 with $k = 1$) for low flows ($i = L$), mean flows ($i = M$), and floods ($i = F$). Points are observed river flows and lines are the scaling relations (in all cases $r > 0.88$ and $p < 0.05$). **(a) Amazon:** $E[Q_L] = \exp(-7.53)LA^{1.08}$; $E[Q_M] = \exp(-4.18)LA^{0.94}$; $E[Q_F] = \exp(-1.70)LA^{0.82}$. **(b) Negro:** $E[Q_L] = \exp(-5.72)LA^{0.99}$; $E[Q_M] = \exp(-3.09)LA^{0.90}$; $E[Q_F] = \exp(-0.71)LA^{0.77}$. **(c) Solimoes:** $E[Q_L] = \exp(-14.75)LA^{1.62}$; $E[Q_M] = \exp(-7.40)LA^{1.18}$; $E[Q_F] = \exp(-2.99)LA^{0.91}$. **(d) Madeira:** $E[Q_L] = \exp(-6.05)LA^{0.93}$; $E[Q_M] = \exp(-4.08)LA^{0.91}$; $E[Q_F] = \exp(-2.00)LA^{0.82}$. **(e) Xingu:** $E[Q_L] = \exp(-11.22)LA^{1.28}$; $E[Q_M] = \exp(-4.05)LA^{0.90}$; $E[Q_F] = \exp(-2.03)LA^{0.83}$. **(f) Tapajos:** $E[Q_L] = \exp(-2.49)LA^{0.75}$; $E[Q_M] = \exp(-3.25)LA^{0.88}$; $E[Q_F] = \exp(-2.80)LA^{0.90}$. For convenience, α_i is expressed as $\exp(\ln(\alpha_i))$.

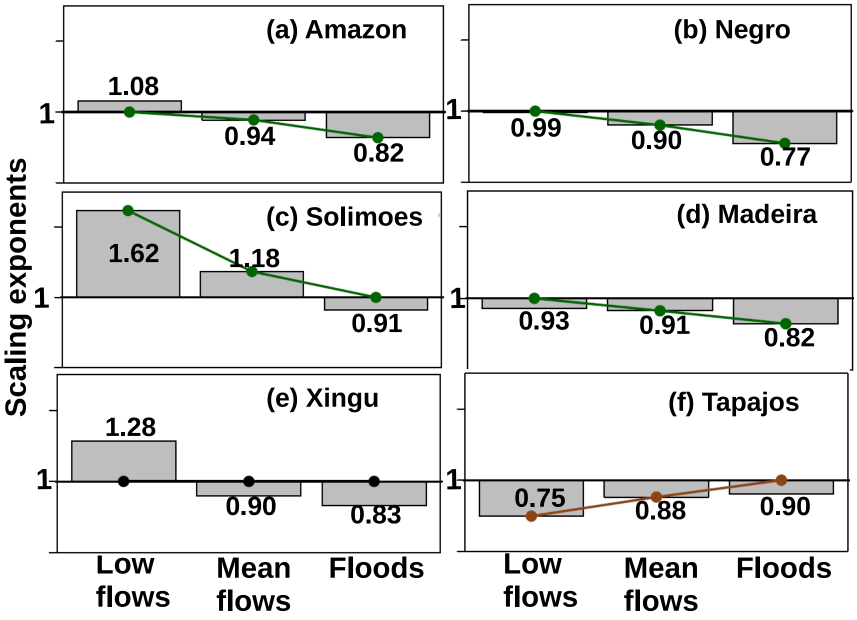

Figure 3. Observed patterns of the values of the scaling exponents for low flows, mean flows, and floods, in the Amazon basin and its six major sub-basins. Dots over the bars indicate whether the exponent values are significantly ($p < 0.05$) different, either higher or lower, from 1. Details about the t-tests are in Supplementary Tables S3 to S8. In regulated states (green, a–d), the exponents decrease from low flows to floods; whereas in unregulated states (brown, f), the exponents increase from low flows to floods. In the Xingu river basin (e), the hypothesis that all exponents are equal to 1 can not be rejected ($p > 0.05$) because of the small number of degrees of freedom (gauges).

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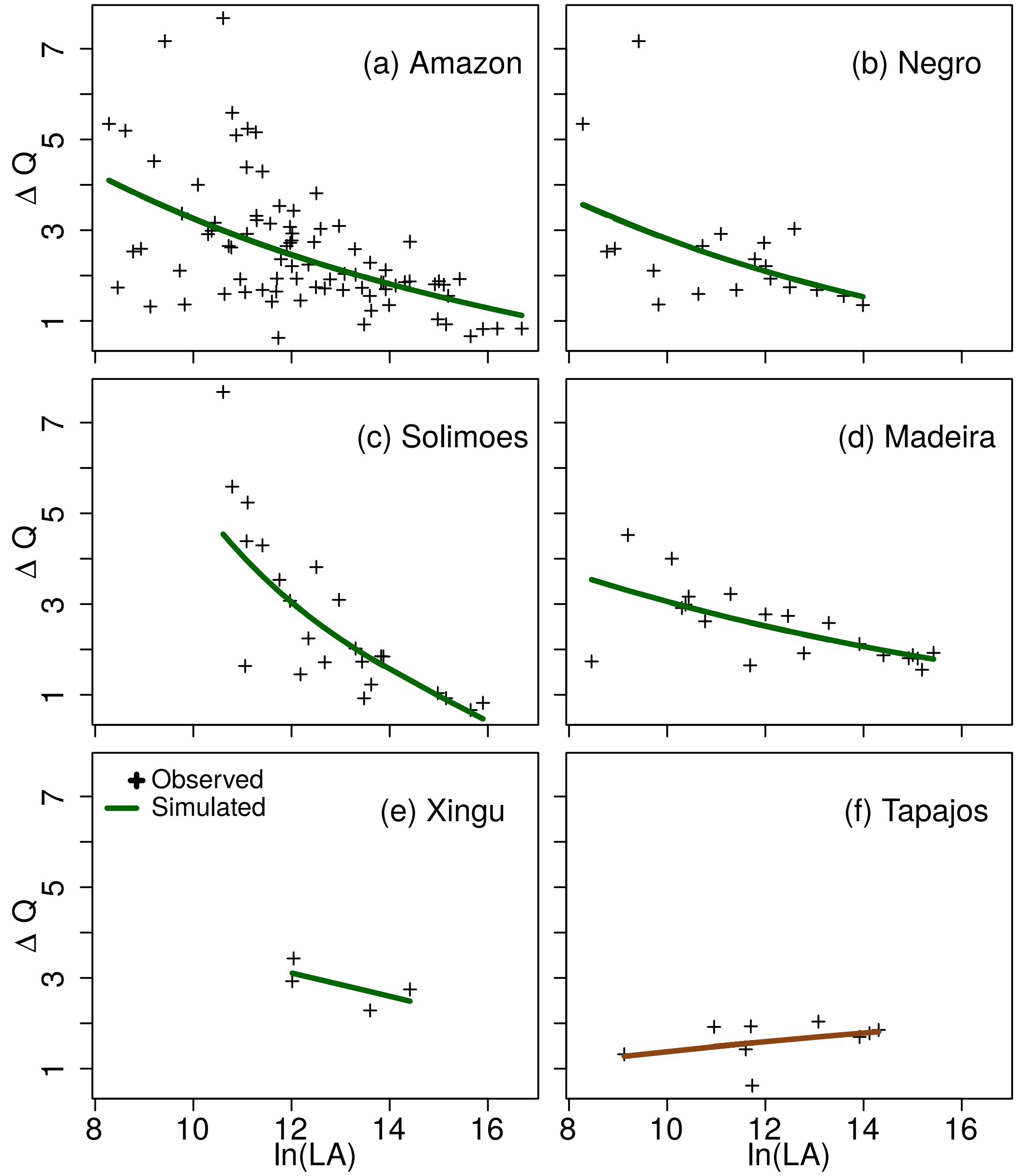

Figure 4. Extremes amplitude, $\Delta_Q = (E[Q_F] - E[Q_L])/E[Q_M]$, as observed (crosses) and simulated (lines) by $(\alpha_F LA^{\beta_F} - \alpha_L LA^{\beta_L})/\alpha_M LA^{\beta_M}$ (from Eq. 2 with $S = LA$), using the scaling parameters of each basin. Δ_Q either decreases or increases with spatial scale (LA) depending on whether the river basin is regulated ($\beta_L > \beta_M > \beta_F$, e.g. Solimoes) or unregulated ($\beta_L < \beta_M < \beta_F$, e.g. Tapajos).

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Table 1. River flow regulation in each basin as revealed by the scaling exponents.

River basin	Scaling exponents	Regulation level ($\beta_L - \beta_F$)	General behaviour of the extremes amplitude (Δ_Q) with increasing scale
Solimoes	$\beta_L >> \beta_M > 1 \geq \beta_F$	Regulated (0.70)	Δ_Q is greatly reduced (regulation) due to the combined effect of low flow amplification ($\beta_L = 1.62 > 1.00$) and flood dampening ($\beta_F = 0.91 \leq 1.00$).
Amazon	$\beta_L \geq 1 > \beta_M > \beta_F$	Regulated (0.26)	Δ_Q is reduced (regulation) due to the combined effect of low flow amplification ($\beta_L = 1.08 \geq 1.00$) and flood dampening ($\beta_F = 0.82 < 1.00$).
Negro	$1 \approx \beta_L > \beta_M > \beta_F$	Regulated (0.22)	Δ_Q is reduced (regulation) due to the dominance of flood dampening ($\beta_F = 0.77 < 1.00$). Low flows are not amplified but grow approximately linearly with scale ($\beta_L = 0.99 \leq 1.00$).
Madeira	$1 \geq \beta_L > \beta_M > \beta_F$	Regulated (0.11)	Δ_Q is reduced (regulation) due to the dominance of flood dampening ($\beta_F = 0.82 < 1.00$). Low flows are not amplified but tend to be reduced with scale ($\beta_L = 0.93 \leq 1.00$).
Tapajos	$\beta_L < \beta_M < \beta_F \leq 1$	Unregulated (-0.16)	Δ_Q is increased (no regulation) because low flows are not amplified but dampened ($\beta_L = 0.75 < 1.00$), more than mean flows ($\beta_M = 0.88 < 1.00$) and floods ($\beta_F = 0.90 \leq 1.00$).

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4 The "Forest Reservoir" Concept

The less regulated river basins, Tapajos and Madeira, are also the ones with less forest cover (Fig. 5a). Forest cover is not an static characteristic of the river basins, so different values of the forest cover fraction can be assigned to each basin depending on the selected data source and time: we use 2003 data from Soares-Filho et al. (2006) (2003 is within the range of all of the studied river flow records). However, what is important to our argument is not the precise value of the forest cover fraction in each basin, but the observation that, among the Amazon tributaries, the Tapajos and Madeira river basins have experienced large forest cover reductions mainly as a result of forest loss and/or degradation along the so-called arc-of-deforestation in south–southeastern Amazonia (Soares-Filho et al., 2006; Asner et al., 2010; Costa and Pires, 2010; Coe et al., 2013). Using 2002–2014 atmospheric water data (ERA-Interim reanalysis, Balsamo et al. (2015)), and 2002–2014 land water data (GRACE, CSR-v 5.0, (Tapley et al., 2004)), we also observed that Tapajos and Madeira are the river basins with the the higher long-term average variability of the terrestrial water storages (amplitude of the Liquid Water Equivalent Thickness, LWET, Fig. 5b), and the lower long-term average amount of water stored in the atmosphere (column-integrated precipitable water, Fig. 5c). Taken together, these characteristics are consistent with a river basin with lower capacity to store water within the coupled land-atmosphere system. These observations led us to propose the "forest reservoir" concept that relates the regulation level of the Amazonian river basins with their forest cover.

The physical causes for a river basin to be regulated or unregulated are summarized by its capacity for storing water and controlling its release. Analogously, the capacity of artificial reservoirs to regulate river flows depends on its capacity for storing water and operation rules about how to release it (Magilligan and Nislow, 2005). 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 (Soares-Filho et al., 2006; Malhi et al., 2008). 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 (Sterling et al., 2013; Coe et al., 2009; Piao et al., 2007), and particularly in the Amazon where the role of forests is so relevant that forest loss could force the system beyond a tipping point (Boers et al., 2017; Hirota et al., 2011; Davidson et al., 2012; Khanna et al., 2017; Lawrence and Vandecar, 2015; Zemp et al., 2017; Sampaio et al., 2007).

The forest reservoir concept describes *the natural capacity of river basins in the Amazon to store water and control its release through land-atmosphere interactions —mainly precipitation recycling— that depend strongly on the presence of forests*. This 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. Although the capacity of the atmosphere to store water is small, its capacity to transport water within a system or between a system and its exterior is huge. In the long term, all continental water comes from the ocean through the atmosphere because the atmospheric fluxes of water are the only ones that flow upstream in river networks, while terrestrial fluxes are directed into the ocean by gravitational forces.

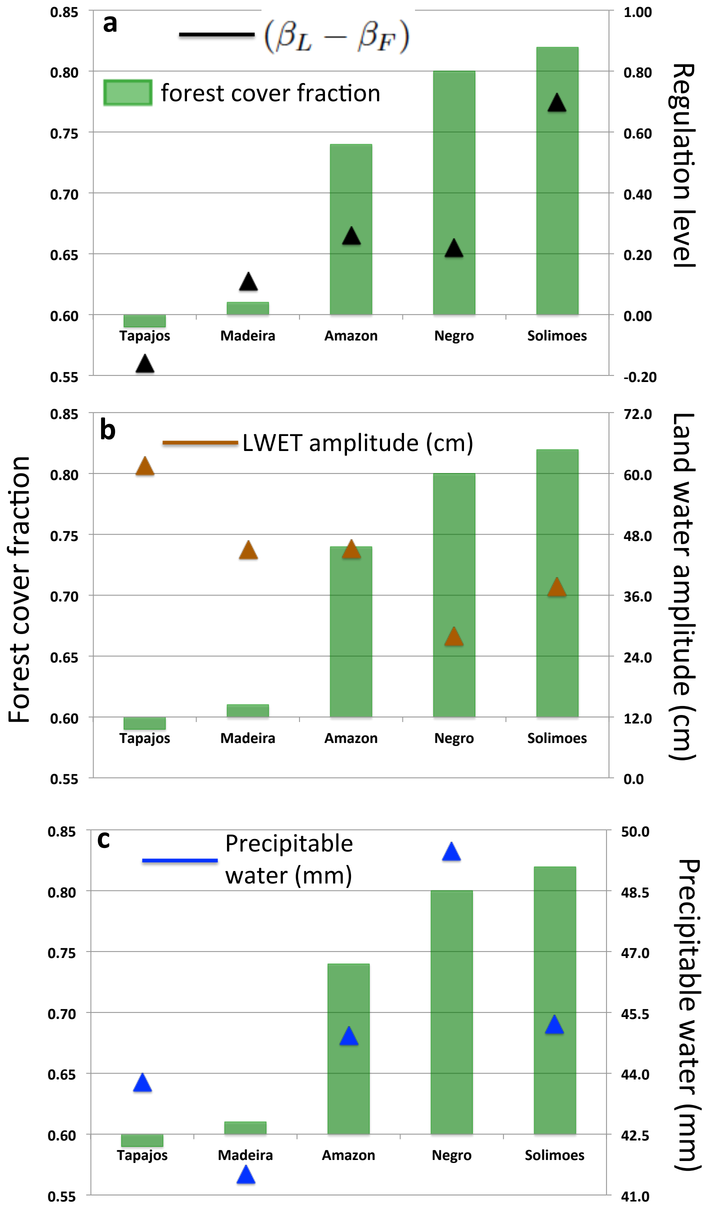

Figure 5. Forest cover fraction (2003 data from Soares-Filho et al. (2006)) and (a) the regulation level ($\beta_L - \beta_F$, this study); (b) the long-term (2002–2014) average variability of the land water storages as indicated by the amplitude of the Liquid Water Equivalent Thickness, LWET (data from GRACE, CSR-v 5.0), and (c) the long-term (2002–2014) average amount of atmospheric water as indicated by the column-integrated precipitable water (data from ERA-Interim reanalysis). The Xingu was excluded because the scaling exponents are not significantly different from 1 (Fig 3e).

Disregarding the land-atmosphere interactions would be particularly misleading in the Amazon because in this region a large portion of precipitation is recycled (Eltahir and Bras, 1994; Van der Ent et al., 2010). Amazonian forest loss can significantly affect river flows through its impact on precipitation (Stickler et al., 2013; Spracklen and Garcia-Carreras, 2015; Lawrence and Vandecar, 2015; Coe et al., 2009; Zemp et al., 2017; Lima et al., 2014). For instance, the simulated impacts of deforestation on river flows can be opposite depending on whether the precipitation response to deforestation is included or not (Coe et al., 2009; Lima et al., 2014). This is a key reason why findings from small river basins about the hydrological effects of forest loss (e.g. from paired catchment studies) cannot be extrapolated to large river basins (Zhang et al., 2016; Ellison et al., 2012; Zhou et al., 2015).

A variety of mechanisms that can enhance the storage of water and control of runoff production in the Amazon are inextricably linked to the presence of forests. These mechanisms include large evapotranspiration fluxes (Da Rocha et al., 2009; von Randow et al., 2012; Caldararu et al., 2012) linked to large precipitation recycling ratios (Eltahir and Bras, 1994; Van der Ent et al., 2010), accumulation and redistribution of soil moisture by root systems (Nadezhdina et al., 2010; Nepstad et al., 1994; Lee et al., 2005), strong capacity for stomatal regulation due to the large cumulative surface area of leaves (Berry et al., 2010; Costa and Foley, 1997), production of biogenic cloud condensation nuclei (Pöschl et al., 2010), below-canopy shading and temperature inversions that restrict direct soil evaporation (Henao et al., Submitted), and the surface drag that is caused by the large height of trees and affects the flow of air over the forests (Khanna et al., 2017). Collectively, these mechanisms imply that Amazonian forests have a strong potential to enhance the capacity of river basins for both storing water and controlling its release.

Figure 6 shows a conceptual model of how forest loss can disrupt the river flow regulation (increase the extremes amplitude) induced by the forest reservoir. Forest loss can exacerbate floods by increasing direct runoff through reduction of the evapotranspiration and infiltration fluxes, associated with a reduced capacity of the coupled land-atmosphere system for retaining water during wet periods (Fig. 6a). During dry periods, forest loss can reduce low flows through reduction of the base flow, associated with a reduction of the capacity of the coupled land-atmosphere system for storing water during wet periods to release it during dry ones. Precipitation reduction and a deforestation-induced lengthening of the dry season (Costa and Pires, 2010; Lima et al., 2014) can further reduce low flows (Fig. 6b).

Any change in the water storage capacity of a river basin can reflect into the long-term river flow regime and therefore in the scaling exponents. The introduction of an artificial reservoir can cause contrasting effects on regulation. Assuming that an artificial reservoir is operated so as to reduce floods and increase low flows, its introduction in a river basin should enhance river flow regulation. However, the construction of reservoirs is usually linked to other human activities —e.g. road construction, and associated agricultural expansion and deforestation (Soares-Filho et al., 2006; Mahe et al., 2005)— that can reduce the natural capacity of river basins to regulate river flows. Our results suggest that this is the case in the Madeira and Tapajos rivers. They are, at the same time, the less regulated basins, the more deforested ones (Coe et al., 2013), and the ones with more large reservoirs in operation (http://dams-info.org/).

There is an increasing body of scientific evidence indicating that large-scale forest loss will reduce precipitation in the Amazon (Stickler et al., 2013; Spracklen and Garcia-Carreras, 2015; Lawrence and Vandecar, 2015; Coe et al., 2009; Zemp

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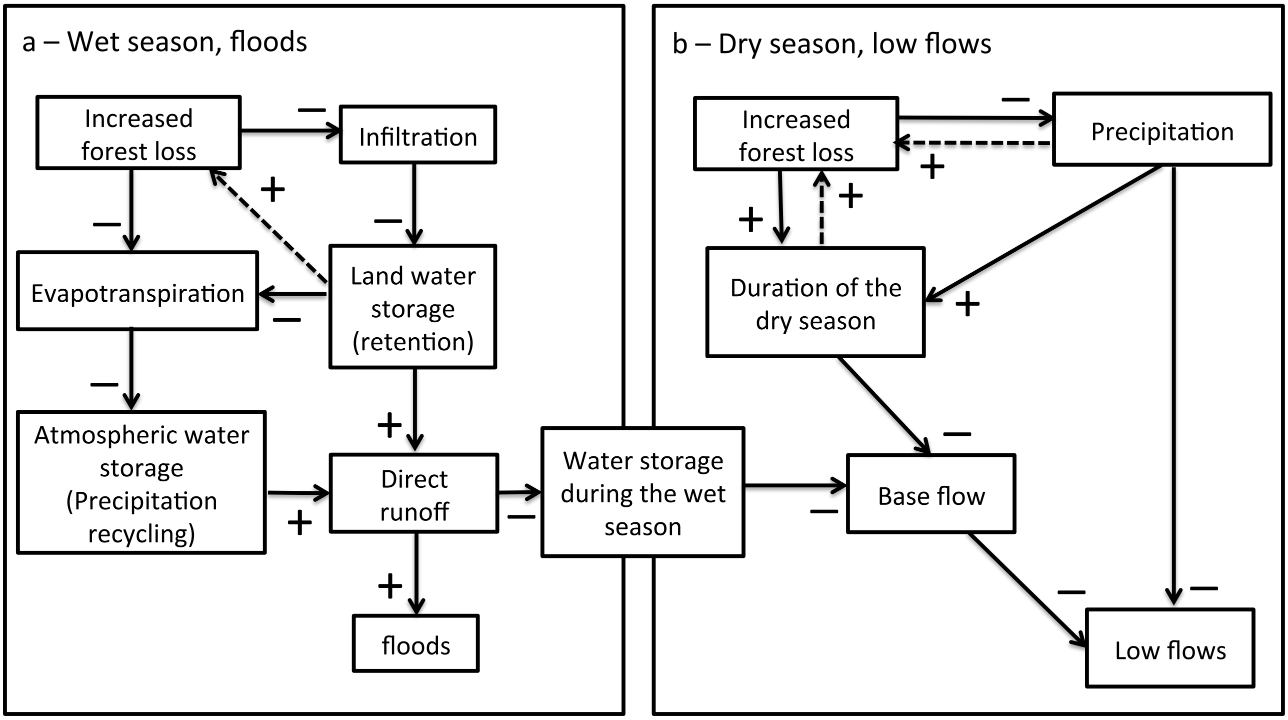

Figure 6. Potential disruption of the forest reservoir due to forest loss. (a) The loss of forests can exacerbate floods through increases of the direct runoff associated with reductions of the evapotranspiration and infiltration fluxes. These effects are associated with a reduction of the capacity of the coupled land-atmosphere system for retaining water during the wet season. (b) Less water retention during the wet season can reduce the base flow during the dry season. The loss of forests can reduce the low flows through reductions of the base flow and precipitation, both of them associated with a reduction of the capacity of the coupled land-atmosphere system for storing and releasing water during different periods of time. Dashed arrows indicate potential positive feedbacks to forest loss.

et al., 2017; Lima et al., 2014; Costa and Pires, 2010). The forest reservoir concept implies that forest loss can reduce low flows while increasing floods. Increased forest loss and reduced precipitation can produce these contrasting effects through interactions between the storage and release mechanisms during the wet and dry seasons (Fig. 6). A comparable situation has been observed in the Nakambe River in Africa where reduced precipitation has lead to the counter-intuitive effect of increased floods, even despite an increase in the number of dams in the river basin (Mahe et al., 2005).

A critical implication of our forest reservoir concept is that forest loss can induce a transition from the regulated state to the unregulated state in the Amazonian river basins. The value of the forest cover fraction where the inequality reverses from $\beta_L > \beta_M > \beta_F$ (regulated state) to $\beta_L < \beta_M < \beta_F$ (unregulated state) is ~ 0.60 (Fig. 5a), equivalent to $\sim 40\%$ deforested area in a river basin. This value is in good agreement with previous studies suggesting that forest loss beyond ~30–50% constitute a critical threshold in the Amazon beyond which rainfall is substantially reduced and a shift in the biosphere-atmosphere equilibrium can occur (Boers et al., 2017; Lawrence and Vandecar, 2015; Hirota et al., 2011; Sampaio et al., 2007). In particular, previous studies have investigated the equilibrium between climate (mainly precipitation) and vegetation, and suggested that tropical forest and savanna represent alternative stable states (attractors) of the biosphere-atmosphere system in the Amazon (Hirota et al., 2011; Malhi et al., 2008; Sampaio et al., 2007; Oyama and Nobre, 2003). Our study is the first to associate such attractors to different states of the river flow regime in Amazonian river basins. Our empirical findings, as well as the forest reservoir concept, indicate that tropical forest and savanna attractors are concurrent with the regulated and unregulated states, respectively: the Tapajos and Madeira are the less regulated basins and also the ones that are closer to the savanna attractor.

5 Conclusions

We have shown how the scaling properties of mean and extreme river flows are a signature of the river flow regime in any river basin. Through the values of the scaling exponents, a river basin can be classified as regulated or unregulated, depending on whether it dampens or amplifies extreme river flows, respectively. These scaling exponents are sensitive to global change, so a river basin can shift from the regulated to the unregulated state. The scaling exponents provide a metric for the proximity to the critical threshold. Our results indicate that environmental perturbations that reduce the natural capacity of river basins to regulate river flows, tend to increase the scaling exponent for floods and to decrease that for low flows. This provides a prediction of the direction of change in the scaling exponents of river basins as a result of global change, that can be used to design and simulate scenarios of future river flow regimes.

In the Amazon, the possible outcome of widespread forest loss remains a matter of great uncertainty and concern (Lawrence and Vandecar, 2015; Boers et al., 2017; Hirota et al., 2011; Davidson et al., 2012; Khanna et al., 2017; Zemp et al., 2017). Our results indicate that forest loss can induce a transition in the river basin from the regulated to the unregulated state. This provides further evidence of a forest critical threshold —equivalent to losing ∼30–50% of the forest cover— in the Amazon (Lawrence and Vandecar, 2015; Hirota et al., 2011; Boers et al., 2017; Sampaio et al., 2007). Our forest reservoir concept provides a parsimonious explanation of the physical mechanisms behind such transition. Progressing towards this understanding is crucial for the detection of early-warning signals for critical transitions in river basins affected by global change. These are urgent needs worldwide (Kéfi et al., 2007; Scheffer et al., 2009; Lenton, 2011; Boers et al., 2017; Hirota et al., 2011; Davidson et al., 2012; Khanna et al., 2017; Lawrence and Vandecar, 2015; Zemp et al., 2017; Sampaio et al., 2007).

These results provide foundations and a quantitative basis for using the scaling theory in solving four fundamental challenges in river basin science: the “PUB problem” that extends to every river basin in a changing environment (Gupta et al., 2007; Hrachowitz et al., 2013); the detection of early-warning signals of critical thresholds in river basins (Lenton, 2011; Scheffer et al., 2009); the production of parsimonious river basin classifications based on dimensionless similarity indices —the scaling exponents— or dominant processes —amplification or dampening of extreme river flows— (McDonnell et al., 2007); and the exploration of the organizing principles that underlie the heterogeneity and complexity of river flow production processes in river basins with different hydroclimatic regimes, and at different scales (McDonnell et al., 2007; Blöschl et al., 2007). We addressed this by advancing from observed patterns (Figs. 2–5) to processes: the forest reservoir concept (Fig. 6) (Sivapalan, 2005). The theoretical basis of our physical interpretation of the scaling properties of river flows is generally applicable to any river basin.

Data availability. All data for this paper is properly cited and referred to in the reference list.

Author contributions. JFS, JCV, AMR and GP designed the research. JFS and AMR developed the mathematical model. JFS, ER, IH and DM performed data analysis. JFS wrote the manuscript with input from other authors. All authors discussed the results and conclusions.

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

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