Global empirical analysis of the role of forest in water surface availability on large basins

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Directors' approval

As co-authors and directors, we certify that we have read the dissertation prepared by Daniel Mercado Bettín entitled "Global empirical analysis of the role of forest in water surface availability on large basins" and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor en Ingeniería Ambiental.

Juan Fernando Salazar | Juan Camilo Villegas

March 2018

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university.

Daniel Mercado Bettín
March 2018

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Dedication

To God.

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Abstract

Water availability is a fundamental element for any society and ecosystem. This availability depends mainly on climate. However, there are other factors that could affect the surface water availability such as soil properties, topography, drainage area and land cover. These factors are approximately invariant except for land cover, which is very sensitive to continuous changes along time. Among the different types of existing land covers, the forest is one of the most important. There is scientific evidence suggesting that forests play an important role in mass, energy and momentum exchanges between atmosphere and surface, which altogether affect surface water availability. Nevertheless, there is also a current debate about the actual importance of forests on water availability. Most of the studies analyzing these effects of forest cover on water yield are developed in a local spatial scale and/or in a short-term period. Accordingly, a research to test the linkage between surface water availability and multiple physical and ecological factors, especially forests, in global large basins was conducted. The main finding of these research is that forests are efficient descriptors of global water balance partitioning. Additionally, after evaluating multiple attributes of the basins and accounting possible bias in the analysis (e.g human intervention by dam construction), forests have a strong relation with water partitioning in tropical and temperate basins, while the snow-melt processes are controlling the partitioning in boreal basins. Finally, after analyzing the effects of climate and land cover changes over streamflow changes using a Budyko-based method in large basins of the world, it is concluded that more studies are required in order to develop a proper approach capable of accounting for all processes in the surface-atmosphere exchanges between vegetation and water balance.

Chapter 1

Introduction

Water availability is a fundamental factor for society and ecosystems. This availability depends mainly on climate regime (Trenberth et al., 2003), but there are other physical and ecological properties that could influence this availability in a short-to-long term scale (Donohue et al., 2006; Rodriguez-Iturbe et al., 2001). The surface water balance is a precise representation to evaluate this water availability, which is represented by streamflow. Streamflows in a river basin are mainly driven by precipitation, but also depend on soil properties, topography, area and land cover (Jencso and McGlynn, 2011; Zhou et al., 2015). These factors are approximately invariant except for land cover, which is the main changing variable that could influence surface water availability, and it is also sensitive to local and global political decisions (Coe et al., 2009; Piao et al., 2007; Spera et al., 2016; Sterling et al., 2013).

Forests are among the most affected ecosystems by human intervention (Hansen et al., 2013, 2010; Malhi et al., 2014) and a relevant factor influencing global water balance (Bonan, 2008; Ellison et al., 2012). There are scientific evidences suggesting that forests play an important role in water, energy and momentum exchanges between atmosphere and surface, which altogether affect surface water availability (Boers et al., 2017; Khanna et al., 2017; Lawrence and Vandecar, 2015; Zemp et al., 2017; Zhang et al., 2016). According to observation analyses, 40% of terrestrial precipitation is produced by land evaporation (Van der Ent et al., 2010); in a forested region such as the Amazon basin, the precipitation recycled is also approximately 40% (Eltahir and Bras, 1994); other biophysical attributes of forests could also influence water availability: effects on precipitation trough condensation nuclei production (Pöschl et al., 2010), enhancement of shallow convection (Wright et al., 2017), induction of cloud formation through atmospheric moisture transport (Fu et al., 2013; Spracklen et al., 2012), evaporation control via stomata (Katul et al., 2012), soil moisture control via canopy properties (Fleischbein et al., 2005), physiological properties to access to energy and water (Nadezhdina et al., 2010) and others. Accordingly, the components of water balance (precipitation, streamflow and evaporation) in a large basin are not independent of forest cover.

However, there is also a important debate about the actual relevance of forest on water availability (Andréassian, 2004; Montanari et al., 2013). There are two different scientific points (Ellison et al., 2012; Zhang et al., 2016): the presence of forest is associated with either increasing or decreasing streamflow. This contradiction among scientific studies highlights the complexity to represent and analyze the relation between forest effects and water balance (Coe et al., 2009; Wei and Zhang, 2010). Accordingly, an empirical analysis in large basins of the world to test these two scientific view-points was implemented following the initial hypothesis proposed.

The initial hypotheses of this thesis is based on recent scientific evidences in large areas that highlight that the forest could exert an important regulatory effects over surface water balance through multiple physical and ecological mechanisms. Accordingly, our main objective was to analyze the relation between the presence of forest and hydrological variables in large basin to find possible patterns between both variable, that could indicate a close association between them. This analysis is condensed in the following three papers (Chapter 2-4).

First, the long-term water balance partitioning in 22 large basins of the world was characterized, and the potential linkage between observed partitioning patterns and the extent of forest cover in the basins was explored. The patterns found are associated with complementary studies, which support the results (Salazar et al. (2017), DMB is co-author in this paper). This approach is in the spirit of linking patterns to processes (Sivapalan, 2005), and of using data-intensive science as a timely and promising paradigm for advancing hydrological science (Peters-Lidard et al., 2017).

Second, the relation between long-term water balance partitioning in 126 large free-flowing rivers basins and key ecological and physical attributes of the basins (soil, topography, area and land cover type) was evaluated. These attributes affect water balance partitioning through surface-atmosphere interaction via evaporation, energy exchange and atmospheric circulation (Stark et al., 2016), surface and sub-surface processes that relate to water retention and infiltration (Saxton et al., 1986), drainage capacity (Beven and Kirkby, 1979), hydrological time response and water distribution in time (McGuire et al., 2005). These relations with the Budyko approach were linked, analyzing the water and energy limitations effects on each basin.

Third, the changes in streamflow trough time and its relation with changes in climate and changes in land cover were analyzed. Traditional (Budyko-based) method to represent these changes in streamflow was applied (Budyko, 1971; Ol'Dekop, 1911; Pike, 1964; Sankarasubramanian et al., 2001; Schreiber, 1904; Turc, 1953; Zheng et al., 2009). Precipitation and potential evaporation are the widely-known variables representing these changes in streamflow. Nevertheless, land cover changes could also affect these streamflow changes. Although a tested method to evaluate both (climate and land cover) effects on streamflow was used, how these methods require some adjustments to account for all key ecohydrological mechanisms associated with vegetation in large basins is discussed.

The connection between the three articles lies in the questions that were appearing along the way, the self-criticisms generated by the authors and the constant suggestions of other scientists. The first article reflects an initial patterns that clearly reflects that the forest represents an important role in the hydrological partitioning of large basins. The second article support the first article, showing that after evaluating multiple physical and ecological factor, that could influence hydrological partitioning, the forest is one of the most relevant factor in this relation, specially in tropical and temperate regions. The third article is an initial approach (using a Budyko-based method) to separate the effects of land cover and climate over streamflow (this is particularly important in large basins), as a conclusion is stated that more studies are required to account for all processes involved in the surface-atmosphere exchanges in large basins. In general, this thesis shows and supports a new and useful patterns, but also opens new questions and challenges.

Chapter 2

Global synthesis of forest cover effects on long-term water balance partitioning in large basins

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Global synthesis of forest cover effects on long-term water balance partitioning in large basins

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Abstract. Global changes in forest cover have been associated with major scientific and social challenges. There are important uncertainties about the potential effects of ongoing forest loss on continental water balances. Here we present an observation-based analysis of long-term water balance partitioning (precipitation divided into evaporation and runoff) in **24** large basins of the world. We identify two partitioning patterns likely related to biophysical mechanisms that depend on the presence and abundance of forests. In less forested basins, evaporation dominates the water balance and, as forest cover increases, this dominance of evaporation over runoff is reduced. When forest is the predominant cover, both components account for nearly half of precipitation in the long-term water balance. The distinction between these two patterns is not fully explained by differences between water- and energy-limited environments, but requires consideration of other biophysical properties that affect precipitation and its conversion into evaporation and runoff. Our results indicate that forest cover is an effective descriptor of basin attributes that are relevant for characterizing long-term water balance partitioning in large basins of the world.

1 Introduction

A major scientific challenge in hydrological sciences is how river flows (and therefore water availability for multiple social and ecological processes) **are influenced by** forest cover (Zhou et al., 2015; Zhang et al., 2016; Berghuijs and Woods, 2016; Ellison et al., 2017). Two contrasting views have been presented for answering this question (Ellison et al., 2012; van der Ent et al., 2012). One view is that the presence of forests causes a decrease in river flows, mainly because forests can support large evaporation fluxes (which includes free surface evaporation and plant transpiration) due to their large cumulative leaf area. A contrasting view is that the presence of forests can lead to an increase of river flows through, for instance, complex land-atmosphere interactions related to feedbacks of vegetation on precipitation (Savenije, 1996, 1995; Wang-Erlandsson et al., 2017; Salazar et al., 2017). Both views are supported by observational and modelling studies (e.g. Zhou et al., 2015; Zhang et al., 2016). For instance, previous studies have reported that forest cover reduction in large basins can result in both increased (Wei and Zhang, 2010) or decreased (Coe et al., 2009) mean river flows. Such contradictory views highlight that there is not a single, globally-applicable response to the fundamental question of the effects of forest cover on river flows. Progressing towards quantitative understanding of the hydrological role of forests is a fundamental step in predicting river flow regimes in a changing environment, especially under the perspective of the "*Panta Rhei*—Everything Flows" debate (Montanari et al., 2013).

One key difficulty in addressing questions about the hydrological and meteorological role of forests in basins arises from scale issues (D'Almeida et al., 2007; Zhang et al., 2016). Of particular importance is that results from small basins (e.g. paired catchment studies) cannot be directly extrapolated to large basins. This **is because the potential occurrence of** complex land-atmosphere interactions that are not observable at the small scale can have important implications for the potential effects of forest cover change on river flows at larger scales (e.g. Stickler et al., 2013; Coe et al., 2009). Precipitation recycling is an important example of such interactions. Global estimates indicate that, on average, 40% of the terrestrial precipitation originates from land evaporation and that 57% of all terrestrial evaporation returns as precipitation over land (Van der Ent et al., 2010). In the Amazon, the largest basin of the world, a large fraction (estimates vary around $\sim 40\%$) of precipitation is recycled (Eltahir and Bras, 1994), i.e. a large fraction of the precipitation falling over the Amazon river basin has been originated as evaporation from forests within the same basin. This and other related phenomena (e.g. production of biogenic cloud condensation nuclei, Pöschl et al. (2010); activation of shallow convection through transpiration, Wright et al. (2017)) establish a physical linkage between the presence of forests and the behaviour of precipitation over the basin. Under this perspective, precipitation in a large basin is not independent of forest cover (they are linked through observable biophysical mechanisms), and evaporation **can**not simply be assumed as a loss for the surface water balance, but rather as a potential component of hydrological regulation mechanisms in the basin (Salazar et al., 2017).

Scale issues and related land-atmosphere interactions can have important practical implications. Coe et al. (2009) showed that, in large tributaries of the Amazon, modeling results about the effects of deforestation on river flows are contradictory depending on whether forest feedbacks on precipitation are considered or not. In particular, they found that simulated river flows are reduced as a consequence of deforestation (with important implications for hydropower generation) when forest feedbacks on precipitation are considered, but not the other way around. The interactive mechanisms that link precipitation and evaporation through continental moisture recycling patterns is importantly related to land cover, and plays an important role in the distribution of global water resources (Van der Ent et al., 2010; Zemp et al., 2017).

The partitioning of long-term water balance (precipitation divided into evaporation and runoff) can be affected by basin attributes which include not only properties that are relatively invariant (e.g. geological properties and river network topology), but also properties that are highly sensitive to global change at policy-relevant time scales (e.g. land cover). Identifying those factors that are both highly sensitive to global change and strongly influential on the partitioning is fundamental for predicting the hydrological effects of global change. Vegetation cover and vegetation-related processes meet these two conditions in many basins of the world (Spera et al., 2016; Sterling et al., 2013; Coe et al., 2009; Piao et al., 2007). **We focus on** forests because these ecosystems are highly threatened worldwide (Hansen et al., 2010, 2013; Malhi et al., 2014; Allen et al., 2015), while there are important uncertainties about the potential consequences of forest loss on continental water balances (e.g. Bonan, 2008; Ellison et al., 2012; van der Ent et al., 2012; Makarieva et al., 2013; Zhang et al., 2016), including the possibility of forest loss tipping points (Lovejoy and Nobre, 2018; Boers et al., 2017; Zemp et al., 2017; Khanna et al., 2017; Lawrence and Vandecar, 2015).

In the the long-term land water balance equation,

$$P = E + R, \quad (1)$$

precipitation (P) is divided into runoff (R) and evaporation (E) fluxes, under the assumption that **variations in** land water storage within the basin are negligible (tend to zero) in the long term (Manabe, 1969; Zhou et al., 2015). The widely recognized Budyko hypothesis defines limits for this partitioning based on the availability of water and energy (Budyko, 1974). The maximum possible actual evaporation (E) is limited by the potential evaporation (E_p), i.e. the available energy. Mass continuity implies that $E + R$ is also limited by the available water, P. However, the specific partitioning pattern in a river basin (the observed values of E and R) depends not only on the availability of water (P) and energy (E_p), but also on the biophysical processes and basin attributes that exert controls on the production of E and R. This implies that same water and energy availability (P and E_p) can occur in basins with different hydrological partitioning patterns (E and R), **which** leads to the important question of how these patterns relate with relevant biophysical attributes of such basins.

Through an observation-based analysis, we characterize **the** long-term water balance partitioning in 24 large basins of the world, and explore the potential linkage between observed partitioning patterns and the extent of forest cover in **these** basins. Our approach is intended to linking patterns to processes (Sivapalan, 2005), and to using data-intensive science as a timely and promising paradigm for advancing hydrological science (Peters-Lidard et al., 2017).

2 Data and methods

The **average** partitioning of P into E and R can be summarized by the *runoff coefficient* k which quantifies the fraction of P that is converted into R, so that $R = kP$ (Sherman, 1932). Using river flow records from **186** gauges distributed among **24** basins of the world (Fig. 1a, Supplementary Table S1), we estimated the value of k at each gauge as $k = R/P$ averaged for the period 2001–2012. R was computed as $R = Q/A$, where Q is long-term average river flow (data from national and international databases, Supplementary Table S2) and A is the drainage area at each gauge. **All river flow records used for the analysis contain at least 10 years in the same 12-year period.** A values were estimated through the best basin delineation generated in the hydrological modules of GRASS GIS (http://grass.osgeo.org/) based on Digital Elevation Models (DEMs) extracted from the GTOPO30 (DAAC, 2004) and SRTM (Jarvis et al., 2008) projects. **River network information was used to correct basin boundaries, which is specially important in regions with very large flat areas such as the Amazon basin.** All differences between the source data and calculated drainage areas were lower than 10%. P was computed as **the spatial average for each basin**, using the Tropical Rainfall Measuring Mission (TRMM-3B42) (Huffman et al., 2007) for tropical basins (Magdalena and Amazon, (Elgamal et al., 2017; Zulkafli et al., 2014)), and the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis (Dee et al., 2011) for the rest of the basins (Betts et al., 2009; Fu et al., 2016; Szczypta et al., 2012; Kalognomou et al., 2013). Potential evaporation (E_p) **was also computed as the spatial average for each basin**, using the Global Land Evaporation Amsterdam Model (GLEAM v3.0a, Martens et al. (2017); Miralles et al. (2011)), **which is**

based on the Priestley-Taylor equation. Our analysis also considers basin internal evaporation recycling ratios (BIER) from Berger et al. (2014).

To provide a metric of forest cover that relates to the statistics of hydrological partitioning in each basin, and considering that vegetation cover is not a static attribute, we constructed a global land cover map (Fig. 1a) using the temporal mode (the most frequent class) for each pixel in the 12-year (2001–2012) map series of MODIS-MCD12C1 (Friedl et al., 2010). Land cover classification was defined after the International Geosphere Biosphere Programme (IGBP) scheme, which divides global land cover into 16 classes. We further grouped them into five classes: (1) Forest, which includes evergreen and deciduous forest types; (2) Shrub-Grass-Savanna, that includes two types of shrub-lands (open and closed), two types of savannas (woody and not) and grasslands; (3) Urban-Crop, that includes croplands, urban zones and cropland/natural mosaics; (4) Water that includes open water areas, wetlands and snow; and (5) Desert that includes barren areas.

To explore potential linkages between water balance partitioning and forest cover, we used a suite of statistical techniques including correlation analysis (using Pearson's, Spearman's and Kendall's correlation methods, Supplementary Table S3) and locally weighted polynomial fittings (LOESS). **To explore for potential biases in the selection of basins, we perform a sensitivity analysis that considers different criteria for the construction of basins samples.**

3 Observed patterns of water balance partitioning

3.1 E-dominated and P-halved patterns

Long-term water balance partitioning (represented by k) and cumulative forest cover fraction vary along the river network of each basin (Fig. 1b). There is no generally-applicable pattern for the variation of k upstream from the outlet of each basin (left to right along the x-axis of Figure 1b), consistent with the spatial variability of P and heterogeneity of the biophysical processes and attributes that affect the production of both E and R.

The basins included in this study differ widely in their environmental characteristics, including geographic location, climatic regimes, geological and geomorphological properties, land cover types **and human-induced disturbance levels.** However, an analysis of the whole set of basins reveals two distinctive patterns of the long-term water balance partitioning. Basins in Figure 2 are ordered, from left to right, by total forest cover fraction (green shading). Box-plots describe the spatial variability of R (Fig. 2a), P (Fig. 2b) and k (Fig. 2c) within each basin. A LOESS fitting ($p < 0.05$, blue line in Fig. 2c) indicates that the mean value of k varies with the forest cover fraction in a way that coincides with two different patterns of water balance partitioning (Equation 2 and Fig. 3): an *E-dominated* pattern ($k < 0.5$, $E > R$) in the less forested basins, and a *P-halved* pattern ($k \approx 0.5$, $E \approx R \approx P/2$) in the more forested basins.

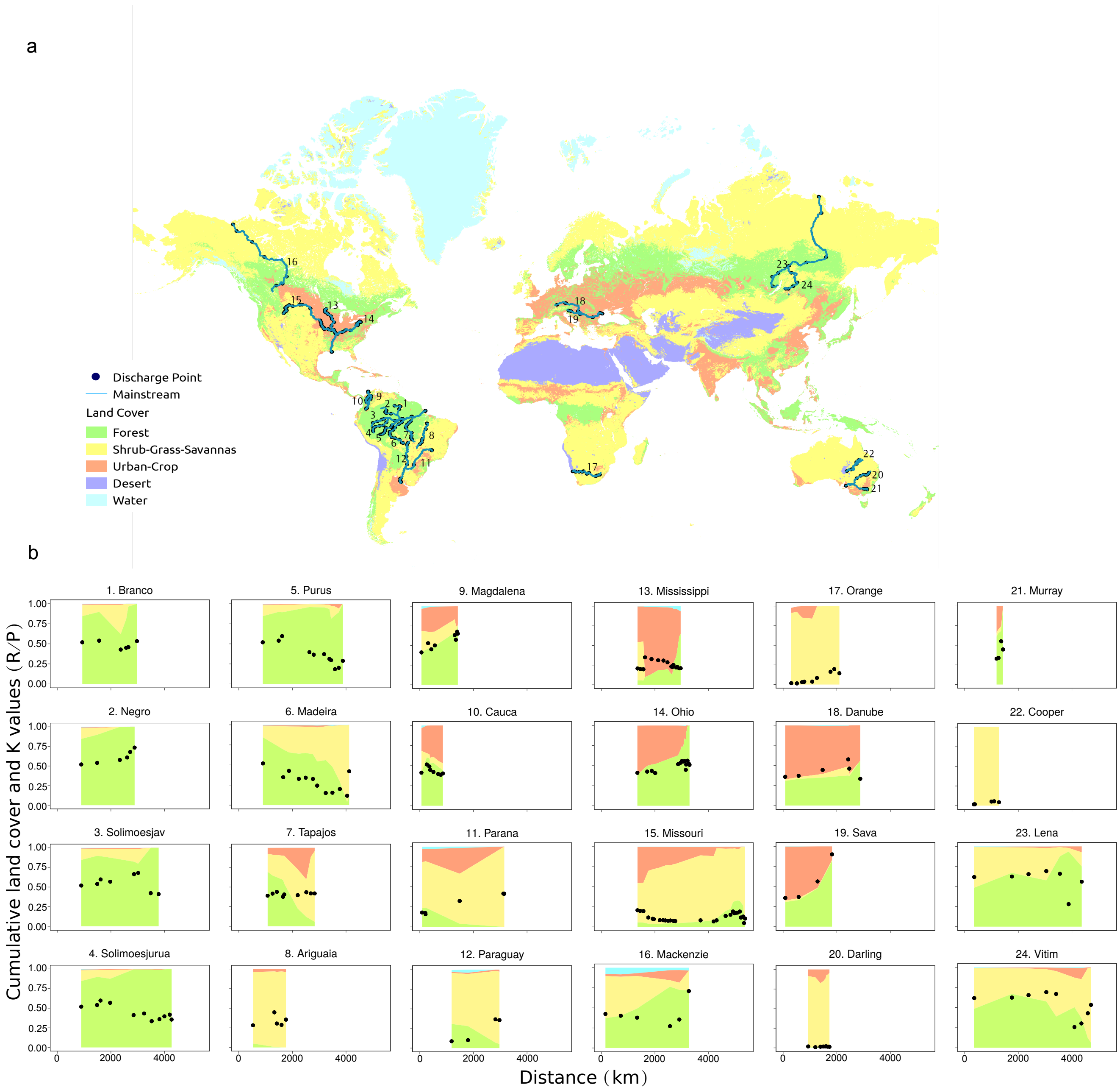

Figure 1. (a) Large basins selected for our analysis and associated global reclassified map of land cover mode (the most frequent class during 2001–2012). Numbers identify each basin for reference in b. **(b)** Cumulative fraction of land cover (spatial average) on each basin as a function of upstream distance to the basin outlet (x-axis). Colours represent the same categories as the map. Black **circles represent** k values **at gauges** along the river network of each basin.

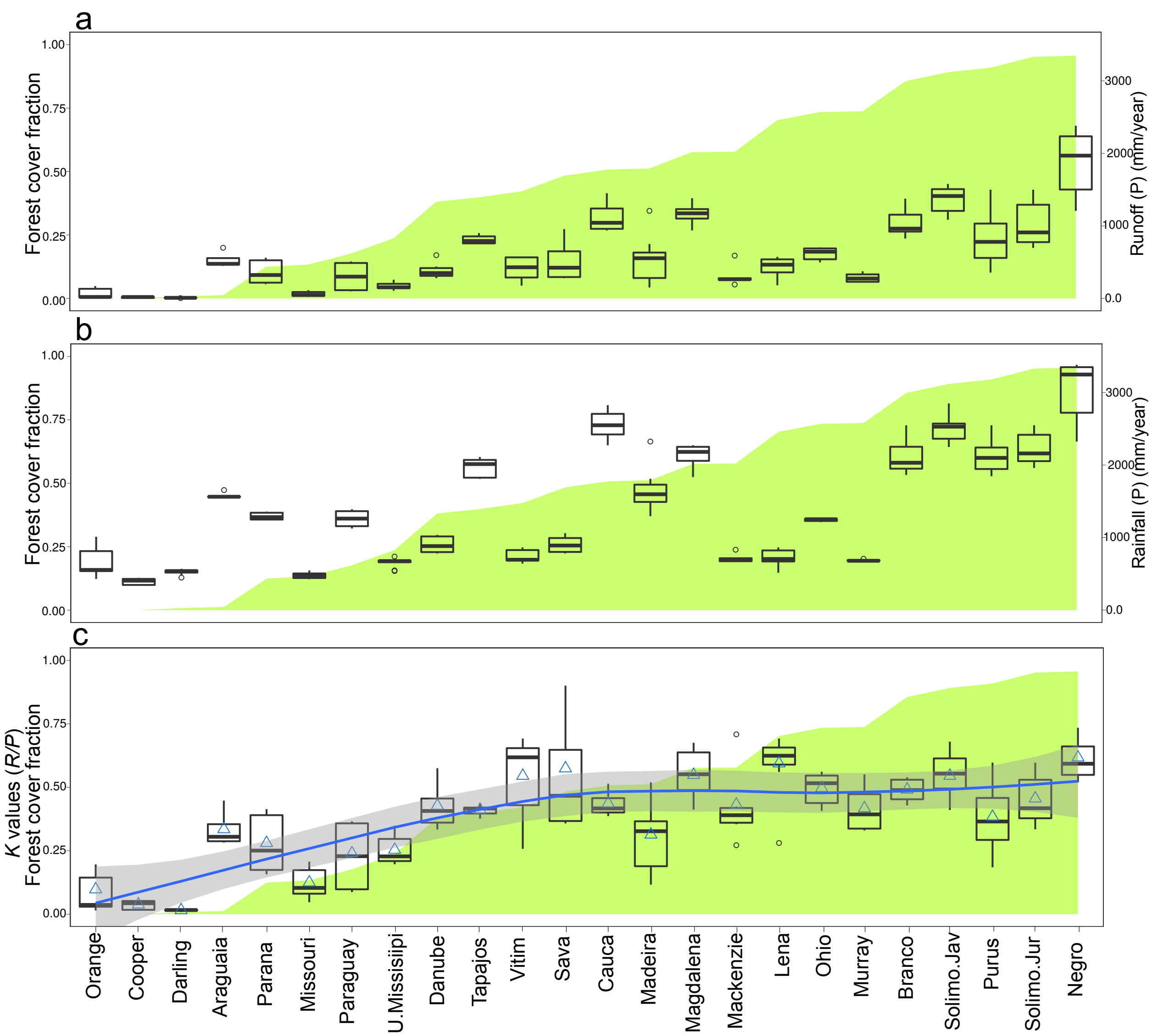

Figure 2. Distribution of spatially averaged R (a), P (b) and k (c) for the **24** basins organized by increasing forest cover fraction (green shade), for the 2001–2012 period. Boxplots describe the spatial variability of R (a), P (b) and k (c) within each basin. In basins with low forest cover fraction, k-mean values (blue triangles) increase with forest cover fraction, with $k < 0.5$: E-dominated pattern. In basins with high forest cover fraction, k-mean values converge to a value around 0.5: P-halved pattern. Blue line is the LOESS fitting and grey shade is the corresponding 95% confidence interval.

The partitioning patterns **shown in Figure 2** correspond to two out of three **theoretically possible patterns**, depending on the value of R/E ratio. Since $R = kP$, mass continuity (Equation 1) implies that $E = (1-k)P$ with $0.0 \leq k \leq 1.0$ and, therefore,

$$\frac{R}{E} = \frac{k}{1-k} \begin{cases} < 1.0, & \text{if } 0.0 \leq k < 0.5 \ \ (E\text{-dominated}) \\ = 1.0, & \text{if } k = 0.5 \ \ (P\text{-halved}) \\ > 1.0, & \text{if } 0.5 < k \leq 1.0 \ \ (R\text{-dominated}), \end{cases} \tag{2}$$

where $0.0 \leq k < 0.5$ indicates that the partitioning pattern is E-dominated, meaning that most of P is converted into E and $R < E$. The opposite occurs if $0.5 < k \leq 1.0$, i.e. the pattern is R-dominated and $R > E$. The only alternative to these patterns is a P-halved pattern in which P is equally divided into R and E ($k = 0.5$). All of these patterns are possible in nature. **The partitioning patterns in any** given river basin can be schematically described by a point in the xy-space showed in Figure 3. **Notably, the observed partitioning patterns in the studied basins are not characterized by k-mean values randomly distributed throughout this space, but** organized in a way that coincides with the E-dominated pattern in the less forested basins, and the P-halved pattern in the more forested ones. The R-dominated pattern is not prevalent among the studied basins.

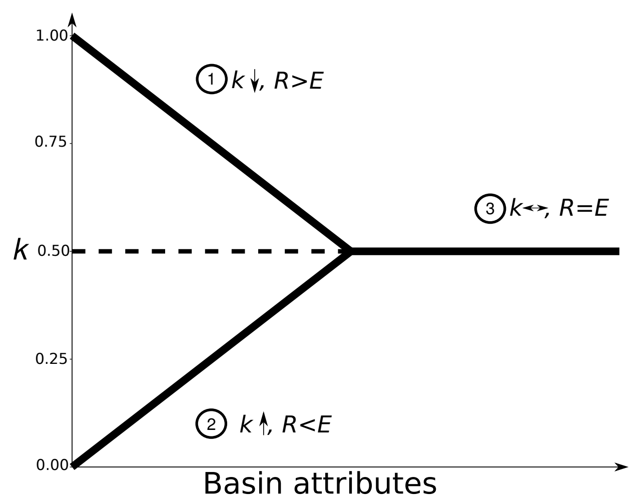

Figure 3. Conceptual patterns of long-term water balance partitioning that can occur in river basins. **Pattern** can be (1) R-dominated ($k > 0.5$), (2) E-dominated ($k < 0.5$), or (3) P-halved ($k = 0.5$), depending on basin attributes schematically represented by the x-axis.

Notably, observed patterns of k do not resemble patterns in neither P nor R. P and R exhibit different relations with forest cover. Same k values can be found in basins with very different P values (e.g. Branco and Ohio), and similar P values can exist in basins with very different k values (e.g. Murray and Darling). This indicates that the variability of k among river basins (the observed patterns), as well as its potential relation with forest cover, emerge from the conversion of P into R, rather than being determined by precipitation patterns alone. A comparison between the Darling and Murray basins illustrates this observation. These basins are located in the same region (they are part of the same large basin), and receive a P-input that exhibits **small spatial variability within the basin** and a similar mean value (Fig. 2b). However, water balance partitioning in the Darling basin (the less forested) is E-dominated, while it is P-halved in the Murray basin (the more forested , Fig. 2c). Another interesting comparison is that between the Missouri, Upper Mississippi and Ohio basins, which belong to the same large basin of the Mississippi river. They are ordered (left-to-right in Fig. 2) by their mean values of P and k, as well as by their forest cover fraction. The Missouri and Upper Mississippi (less forested) basins are E-dominated, while the Ohio basin (more forested) is P-halved. In this case not only k, but also P and R grow with increasing forest cover. Among these three basins, the maximum k value is close to 0.5 and occurs in the more forested basin: Ohio.

Overall, the studied basins can be generally divided into two different groups depending on their long-term partitioning pattern. Basins in the first group (from Orange to Cauca) are characterized by k values that are generally lower than 0.5 (an E-dominated partitioning pattern), and forest cover fractions that are also lower than 0.5. Among these basins, we found a significant and positive correlation between k and forest cover fraction ($\rho = 0.79$, $p < 0.0001$, Supplementary Tables S4 and S5). This regression model was used to separate both groups of basins: it was fitted up until the point where correlation was maximized, corresponding to the Cauca basin. Basins in the second group (from Cauca to Negro) are characterized by k values that are generally close to 0.5 (a P-halved partitioning pattern), and forest cover fractions that are higher than 0.5. **The difference between these two patterns indicates that an increased (a decreased) presence of forests coincides with an enhanced (reduced) capacity of river basins to convert P into R, i.e. with an increased (decreased) k.**

Independent of the potential mechanisms relating water balance partitioning and forest cover, the observed patterns challenge the view that the presence of forests **implies a reduction in river flows (the "demand-side thinking" as described by Ellison et al. (2012)). Instead, our results show that the presence of forests coincides with an enhanced capacity of river basins to convert P into R, i.e. with an increased k. Increased k (linked to increased forest cover) does not necessarily imply, but is nevertheless compatible with increased river flows (the "supply-side thinking", Ellison et al. (2012)).**

3.2 Sensitivity analysis for the selection of basins

The initial selection of 24 basins (Figs. 1 and 2) follows three main criteria: (i) data availability: we constructed a database as a result of combining multiple data sources; (ii) basin size: only large basins were considered; and (iii) spatial distribution of gauges: we used several gauges to describe spatial variability (see, e.g. box plots in Fig. 2) at different scales along the river network (e.g. a large basin with a single gauging station does not allow to consider spatial variability). We did not consider each gauge as an individual basin because our analysis requires statistical independence between basins (the 24 basins) and nested basins are not independent. That is why we used a single descriptor (e.g. the k-mean value) for each one of the independent 24 basins shown in Figure 2.

To explore for potential biases in the selection of basins, we used a random selection method to construct multiple samples with sample sizes (number of basins) varying between 10 and 23. We constructed 23 different sets of basins for each sample size (23 is the number of different samples with 23 basins that can be constructed from a set of 24 basins). Patterns in Figure 4 (which shows the LOESS fittings for randomly selected basin samples) are similar to those

shown in Figure 2. The relation between low (high) k values and less (more) forest cover, as well as the prevalence of k values that are lower or equal than 0.5, are also preserved when grouping basins by size (drainage area) ranges (Fig. 5). However, these features of the E-dominated vs. P-halved patterns are less evident in the smaller basins (Fig. 5a,b), thus suggesting that there may be some scale-dependence in the partitioning patterns. This highlights the need for future research to determine the linkages between partitioning patterns and forest cover in small basins, as well as to explore the existence of scale thresholds.

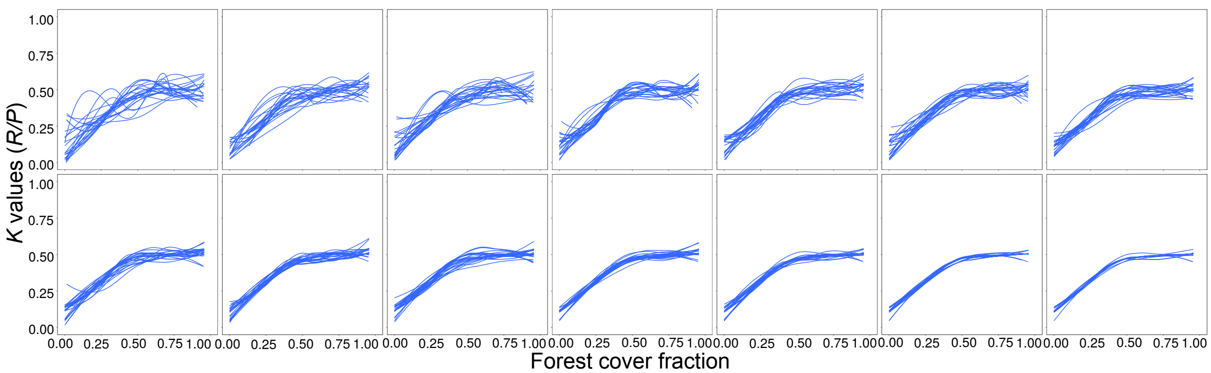

Figure 4. Sensitivity analysis for the selection of basins. Each panel shows the LOESS fitting relating k and forest cover fraction for randomly selected basin samples with sample sizes (number of basins) varying between 10 (top-left) and 23 (bottom-right). For each sample size, there are 23 randomly selected samples.

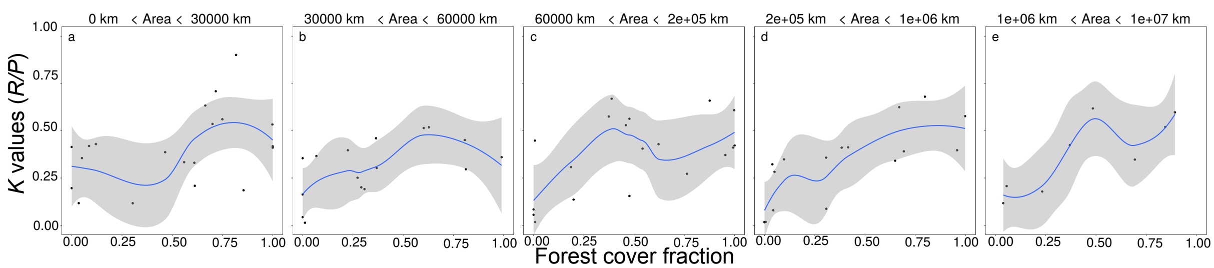

Figure 5. Sensitivity analysis for the selection of basins based on drainage area. Each panel shows the LOESS fitting relating k and forest cover fraction for different basin size ranges. Every point in each panel represents an independent basin (not nested within any of the other basins in the same sample) with the largest possible area (without exceeding the upper limit of the corresponding basin size range).

Studying large basins implies that the influence of multiple interacting factors, including human intervention, cannot be entirely removed (Zhang et al., 2016). Therefore, human disturbances should be part of a comprehensive explanation for the occurrence of different partitioning patterns in large basins. Disentangling this potential human influence is a major challenge that goes beyond our present scope. However, we explore how the observed patterns change with different levels of human disturbance on river flows, and found that excluding basins with large water transfers outside

of the river basin (i.e. using only those basins included in Table S6) result in partitioning patterns (Fig. S1 and Tables S7-9) that largely coincide with those shown in Figure 2. Similar partitioning patterns are found if basins with very high levels of human intervention (Parana, Mississippi, Ohio, Missouri, Orange, Danube, Sava, Darling, Murray) are added (randomly) to the sample (Fig. S2). Collectively, previous results show that general partitioning patterns are preserved despite variations in the selection of basins.

4 Discussion

4.1 Water- and energy-limited environments

The Budyko hypothesis allows to classify hydrological systems, including river basins, as water- or energy-limited, depending on whether the ratio between potential evaporation (E_p representing available energy) and precipitation (P representing available water) is greater or lower than 1, respectively. **From this perspective,** the observed patterns in water balance partitioning (k) are not directly the result of neither water (P, Fig. 2b) nor energy availability (E_p, Fig. 6a). The same P-values can be associated with different partitioning patterns (e.g. Murray and Darling), and same partitioning patterns can be found in basins with different P-values (e.g. Lena and Branco). Indeed, the P-halved pattern is common to basins where P varies from less than 1,000 mm/year to more than 2,000 mm/yr (Fig. 2). Similarly, differences in E_p between less-forested and more-forested basins (Fig. 6a) do not coincide with the distinction between E-dominated and P-halved patterns (Fig. 6c). Same values of E_p can be associated with different partitioning patterns (e.g. **Negro vs. Cooper, and Ohio vs. Missouri**).

The E_p/P ratio (Fig. 6b) and the partitioning pattern (k, Fig. 6c) are not independent because they both depend on P. Less forested basins, where the partitioning pattern is E-dominated, are generally closer to water-limited environments ($E_p/P > 1$); while the more forested basins, where the partitioning pattern is P-halved, are more concentrated in the region of energy-limited environments ($E_p/P < 1$). However, variations in E_p/P do not entirely coincide with the observed partitioning patterns. The E-dominated pattern does not only occur in water-limited, less-forested, basins (exceptions include Parana, Paraguay and Upper Mississippi where $E_p/P \leq 1$), and the P-halved pattern is not exclusive of energy-limited, more-forested, basins (e.g. Murray is not energy-limited but its partitioning pattern is P-halved).

Most (but not all) of the more forested basins are energy-limited environments (Fig. 6b). This implies that there is an excess of water in the surface that could be transformed into runoff, likely leading to an R-dominated pattern. However, the R-dominated pattern is not prevalent in the more forested basins (a few exceptions include some gauges in the Sava river where k reaches values around 0.75, although the mean value is still close to 0.5). Instead, these basins exhibit a partitioning pattern closer to P-halved. This leads to the question of why the excess of water availability in the more forested, energy-limited, basins does not result in an R-dominated pattern. We hypothesize that this is related to the role of forests in regulating the surface water balance, as discussed in the next section.

In summary, the observed distinction between E-dominated and P-halved partitioning patterns is not equivalent to the distinction between water- and energy-limited environments. Under the perspective of the Budyko hypothesis, **for a given** P, an increase of E_p would force the partitioning towards an E-dominated pattern, while decreasing E_p should favour the occur-

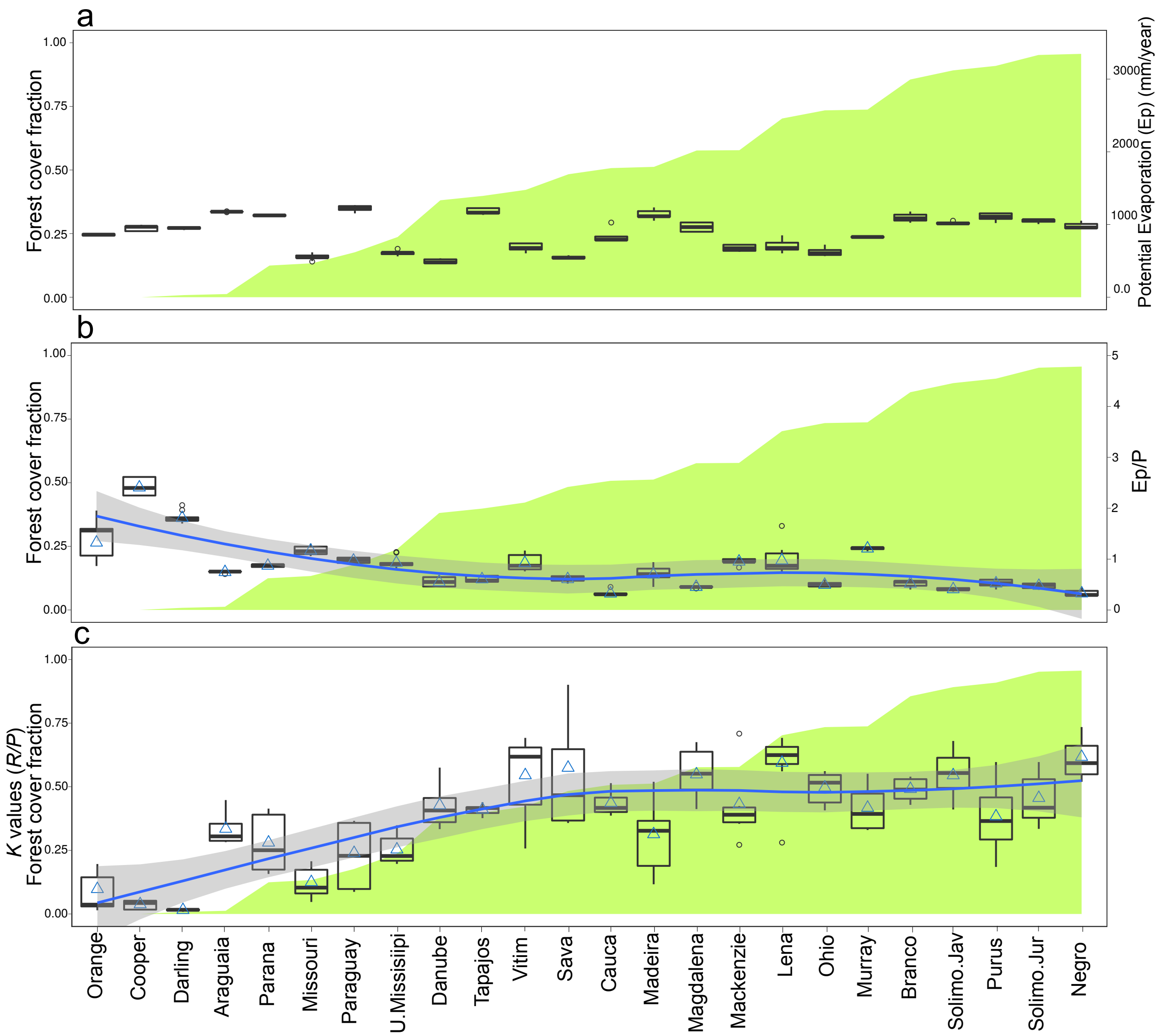

Figure 6. Distribution of spatially averaged E_p (a), E_p/P (b) and k (c; same as Fig. 2c) for the **24** basins organized by increasing forest cover fraction (green shade), for the 2001–2012 period. Boxplots describe the spatial variability of E_p (a), E_p/P (b) and k within each basin. Blue lines are the LOESS fittings and grey shades are the corresponding 95% confidence interval.

rence of an R-dominated pattern. The reasons for the occurrence of a P-halved pattern are less evident from this perspective, because such a partitioning pattern requires an approximate balance between E- and R-production processes. These processes, synthesized by k, depend on biophysical mechanisms and basin attributes that are not fully incorporated in the E_p/P ratio. The long-term water balance partitioning depends not only on the available water (P) and energy (E_p), but also on biophysical processes that are determinant for real evaporation (E) and runoff (R). Of note is also that P (water availability) is not a given amount of water that is independent of the presence of forests in large basins (Spracklen and Garcia-Carreras, 2015).

4.2 The role of forests

The observed partitioning patterns indicate that k increases with forest cover (in the less forested basins), but then it approximately stabilizes around $k \sim 0.5$ (in the more forested basins; Fig. 2). This leads to the question of whether and how these partitioning patterns are related to the presence of forests. **In principle, forests have potential to influence partitioning patterns through a variety of mechanisms including but not limited to:** accumulation and redistribution of soil moisture by root systems (Nadezhdina et al., 2010; Nepstad et al., 1994; Lee et al., 2005; Bond et al., 2002), strong capacity for stomatal regulation related to the large cumulative surface area of leaves (Berry et al., 2010; Costa and Foley, 1997; Katul et al., 2012), land-atmosphere interactions that enhance the capacity of river basins to store water as a natural "reservoir" (Salazar et al., 2017), activation of shallow convection through transpiration (Wright et al., 2017), soil moisture control via canopy effects on hydrological partitioning (Fleischbein et al., 2005), physiological adaptations for water and light use efficiency (Nadezhdina et al., 2010), landscape-scale energy balance effects and overall dynamics of E (Villegas et al., 2014), **and variations in land surface albedo (Betts, 2000; Bastable et al., 1993).**

As a result of the mechanisms through which forests can affect the dynamics of P, E and R in a river basin, the potential influence of forests on partitioning patterns has a complex and dynamic nature. As a first-level explanation (detailed studies are required for producing site-specific explanations), we propose that partitioning patterns emerge from a competition between the two dominant forms of energy that drive the hydrological cycle: radiation and gravitational energy (Fig. 7). Radiation drives E (a land-to-atmosphere flow of water) while gravitational energy drives R (a flow of water directed from land to ocean). The occurrence of an E-dominated pattern ($E > R$) in a basin indicates that the effect of radiation on the production of E dominates over the effect of gravitational energy on the generation of R, otherwise E would not be greater than R. This dominance is reduced as the relative influence of gravitational energy increases, which allows the occurrence of P-halved ($E \approx R$) or R-dominated ($E < R$) patterns. Our results indicate that an increased presence of forests reduces the dominance of radiation over gravitational energy. Figure 7 provides a conceptual example of how the relative dominance between radiation and gravitational energy may lead to different partitioning patterns. In arid and semiarid basins, dominance of radiation may result in an E-dominated pattern, while in basins where drainage is strongly controlled by physical factors such as steep slopes and snowmelt processes, dominance of gravitational energy may induce an R-dominated pattern. In forested basins, complex and dynamic interactions between competing mechanisms allows the occurrence of a P-halved pattern, which indicates an approximate balance between the effects of radiation and gravitational energy.

Important for the possible occurrence of P-halved patterns in largely forested basins is that the long-term effect of forests on the production of E or R is not in a single direction. The presence of forest cover in a basin does not always translate into increased E and reduced R; the effect may be in the opposite direction as well (Teuling et al., 2010). This is a consequence of the dual capacity of forests to either increase or decrease the components of the long-term water balance. For instance, forests

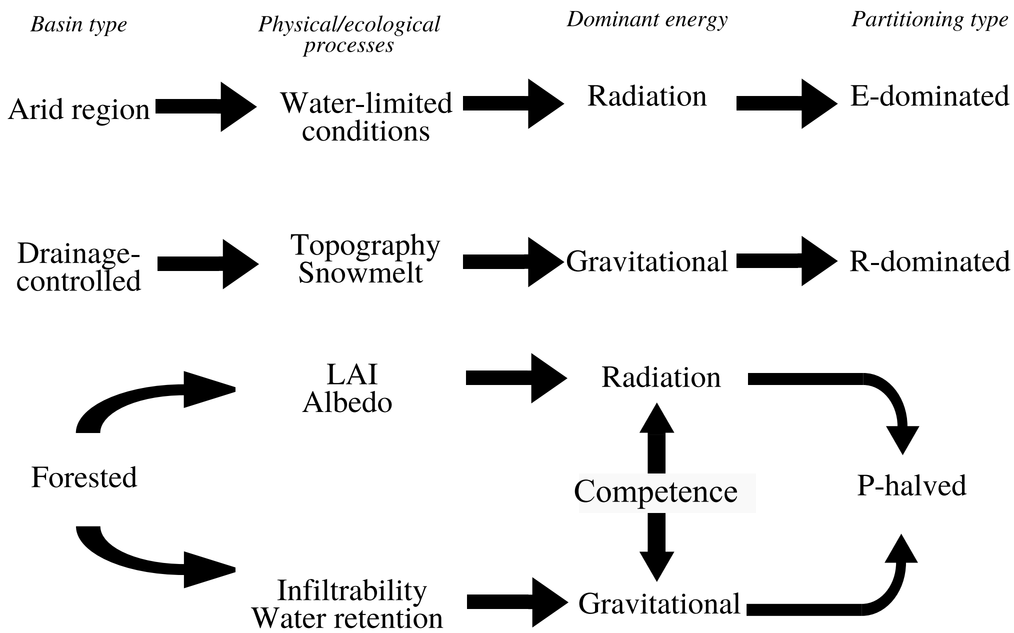

Figure 7. Conceptual example of competing effects from radiation and gravitational energy that lead to different partitioning patterns. Dominance of radiation results in an E-dominated pattern, while dominance of gravitational energy leads to an R-dominated pattern. Forest-related mechanisms allow the emergence of a P-halved pattern through competition between effects from radiation and gravitational energy.

can increase or decrease E via physiological adaptations for controlling transpiration. If the effect of forests were always to increase E, then the increase of forest cover should be associated with an increase of the relative dominance of E over R (i.e. a reduction of k), consistent with a transition from an R-dominated to an E-dominated pattern. This is **challenged by the observations that in the less forested basins k increases with forest cover, and that the increase of k with increasing forest cover is not unlimited (Fig. 2c): there is not a transition between an E-dominated pattern in the less forested basins to an R-dominated pattern in the more forested basins.**

The dual capacity of forests to increase or decrease the water balance components implies that the increase of forest cover **can enhance the capacity of a basin to produce both E and R. Since E and R are competing water fluxes, such a dual capacity allows for the occurrence of E-dominated and P-halved patterns in less or more forested basins, respectively. The increase of k with increasing forest cover may result from interplay between mechanisms that restrict the conversion of radiation into latent heat (via e.g. stomatal regulation, below canopy shading and stability, and aerodynamic resistance associated with the presence of trees), and mechanisms that enhance the retention of water in land and its routing towards river networks (e.g. increased infiltrability and reduced runoff speed; Jinzhao et al. (2002); Zimmermann et al. (2006)). An approximate balance between these type of mechanisms that affect the production of E and R leads to the P-halved pattern. Our results indicate that such a balance is approached as the forest cover fraction increases.**

The approximate balance between E and R in the more forested basins is suggestive of regulation mechanisms acting on the long-term water balance partitioning. The capacity of a river basin to regulate the components of the surface water balance is summarized by its capacity for storing water and controlling its release. This is analogous to the capacity of artificial reservoirs to regulate river flows, which 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, which depend importantly (but not exclusively) on their geological and geomorphological properties (Bruijnzeel, 2004; Miguez-Macho and Fan, 2012). However, the observation that the P-halved pattern is common to basins that differ widely in their geological and geomorphological properties suggests that the occurrence of this pattern is also related to other properties. A common feature of basins exhibiting the P-halved pattern is that they are mostly covered by forests (forest cover fraction is larger than ~ 0.5). The abundance of forests is likely to enhance the natural capacity of large river basins to store water and control its release through land-atmosphere interactions, thereby enhancing the capacity for regulating **the water balance components** (Salazar et al., 2017).

The capacity of forests to increase or decrease the water balance components is also **consistent with the observation that** the R-dominated partitioning pattern is generally absent in more forested basins. Not finding the R-dominated pattern indicates that E-production is generally dominant across the basins (a usual feature of natural ecosystems; Huxman et al. (2005)), with the less dominance when the pattern is P-halved. In less forested basins, most P is converted into E leading to values of k that approach zero as forest cover fraction reduces, corresponding to water-limited environments (Shen and Chen, 2010). A reduction of forest cover reduces the natural capacity of a basin to retain water in the surface (including the ecologically-active root zone in the soil), thereby favoring the conversion of available energy (E_p) into latent heat (E), resulting in a relative reduction of the fraction of P that is potentially converted into R. R-production (we are considering river runoff after accumulation along the river network, $R = Q/A$) is a slower process that requires the accumulation of runoff through surface and subsurface flows. In large basins, a characteristic time-scale for R-production ranges from 10^{-1} to 10^{2} days (or even longer), as given by either the concentration time (e.g. Fang et al., 2008) or the water residence time (e.g. McGuire et al., 2005). As compared to E, enhancing R requires a longer time of residence of water in the surface. Forests have a strong potential to enhance this residence time by restraining E, as well as by favouring the retention of water and its slow routing to river networks (Jinzhao et al., 2002; Zimmermann et al., 2006).

The long-term effect of forests is not only on E and R but also on P. Continental precipitation (and therefore water availability in the Budyko framework) is not independent of the presence of forests —among the studied basins, correlation between P and forest cover fraction is 0.74 ($p = 0.0001$)—. Different perspectives could be used to explain this relation. One view is that forests tend to grow in regions with relatively high water availability, consistent with observation that the more forested basins are not limited by water but by energy (Fig. 6b). However, this view implicitly assumes that water availability in a river basin (especially the precipitation pattern) precedes (it is the cause for) the existence of forests (the effect) and, therefore, that precipitation is largely independent of the presence of forests itself. This is challenged by increasing scientific evidence that forest cover change can significantly alter precipitation regimes in many regions of the world (e.g. Mahmood et al., 2014; Spracklen and Garcia-Carreras, 2015; Lawrence and Vandecar, 2015; Zemp et al., 2017), and that land evaporation is a large source for continental precipitation (Van der Ent et al., 2010; Gimeno et al., 2012) **in which** forests are major contributors (Bonan, 2008; Schlesinger and Jasechko, 2014). If precipitation regimes were independent of forest-related ecohydrological processes, those regimes should not significantly change in response to forest cover change.

As a consequence of the potential feedbacks between P and forest-related processes, increased E over forests does not necessarily imply a long-term reduction in R (e.g. Coe et al., 2009), but rather it can be a component of a transport mechanism that redistributes moisture across a basin (Salazar et al., 2017). Increased E can enhance upstream (downwind) P through atmospheric moisture transport related to precipitation recycling (Zemp et al., 2017; Makarieva et al., 2013; Spracklen et al., 2012). Although more detailed studies are required to assess precipitation recycling in each of the studied basins (this is challenging because precipitation recycling 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 (Van der Ent and Savenije, 2011)), we note that the more forested basins tend to have higher *basin internal evaporation recycling ratios*, BIER (Berger et al., 2014) (Supplementary Fig. S3). This generally agrees with previous studies indicating that recycled precipitation is a major component of large basins with extensive forest cover such as the Amazon (Eltahir and Bras, 1994; Zemp et al., 2017).

A fundamental challenge in quantifying hydrological response (e.g. variations in the water balance partitioning) to forest cover change is to exclude the effect of non-forest drivers on runoff (Renner et al., 2014). This can be even more challenging for large basins with various confounding factors including artificial reservoirs and associated water resources schemes (Zhang et al., 2016). Although more-detailed studies are essential to understand water balance partitioning dynamics in different basins, as well as to characterize the influence of forest and non-forest drivers, our observation-based analysis allows to infer that variations in water balance partitioning patterns are related to variations in forest cover. Observed differences between partitioning patterns in more or less forested basins cannot be directly attributed to the effect of forests on the long-term water balance partitioning in large basins, as correlation does not necessarily imply causation. However, a growing body of scientific literature relates forest cover changes (e.g. deforestation) with alterations in river flow regimes (e.g. Sterling et al., 2013; Stickler et al., 2013; Zhou et al., 2015; Berghuijs and Woods, 2016; Zhang et al., 2016), thereby implying that statistical correlations between river flow- and forest cover-related variables are not necessarily spurious, but rather can be a consequence of forest-related biophysical mechanisms. This is in the spirit of the general idea that, due to the potential effects of many confounding factors that can affect river flows in large basins, and the associated uncertainty of any method, we can only draw statistical inference about the hydrological effects of forests (Zhang et al., 2016). Such empirical approaches are essential because it is becoming clear that accurate mechanistic models to predict hydrological response to forest cover change at multiple spatial and temporal scales are currently beyond our reach (Zhang et al., 2016), and predicting this response remains a fundamental challenge in environmental science today (Ellison et al., 2012; van der Ent et al., 2012; Montanari et al., 2013; Zhang et al., 2016).

5 Conclusion

In synthesis, our results highlight the potential occurrence of two dominant patterns (described by k) in the long-term water balance partitioning (E-dominated and P-halved) occurring in large basins of the world. The occurrence of these two patterns largely coincides with the distinction between less forested and more forested basins. The distinction between the E-dominated and P-halved patterns is related but not fully explained by differences between water- and energy-limitations. Instead, the occurrence of any specific partitioning pattern in a given basin depends on the biophysical processes and basin attributes that affect P, as well as its conversion into either E or R. Further, our results indicate that forest cover is an effective descriptor of those basin attributes that are relevant for characterizing long-term water balance partitioning in large basins of the world.

Overall, our results support the view that the presence of forests enhances the capacity of large river basins to transform P into R, likely as a consequence of forest-related competing mechanisms that tend to balance the effect of radiation and gravitational energy on the generation of E and R. This implies that a potential impact of forest cover change is a change in the water balance partitioning pattern (e.g. from P-halved to E-dominated as a consequence of forest loss) in large basins, thereby affecting river flow regimes that are determinant for many ecological and societal processes (Piao et al., 2007; Coe et al., 2009; Sterling et al., 2013; Lima et al., 2014; Zhang et al., 2016).

6 Data availability

Data used for this study are available through the lead author (daniel.mercado@udea.edu.co).

Author contributions. D. Mercado-Bettín, J. F. Salazar and J. C. Villegas designed the research, discussed the results and wrote the manuscript; D. Mercado-Bettín performed data analysis.

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

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Chapter 3

Long-term water balance partitioning explained by physical and ecological characteristics in free-flowing river basins of the world

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RESEARCH ARTICLE

Long-term water balance partitioning explained by physical and ecological characteristics in free-flowing river basins of the world†

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Summary

For decades, scientists have debated the influence of basin physical attributes and vegetation in the partitioning of rainfall into evaporation (E) and runoff (R). Physical and ecological processes explain long-term behavior of E via water or energy limitations. Needed are similar frameworks for describing the production of streamflow and its interaction with factors influencing E to produce long-term patterns of E-R partitioning. However, studies relating these effects on streamflow are generally local-to-regional in scope and do not explain global patterns of hydrological partitioning. Here we analyze 126 independent and free-flowing river basins in three major regions of the world (tropical, temperate and boreal). We relate water balance partitioning with physical and ecological attributes. Our results indicate that E-R partitioning is significantly associated with the amount of shrub-grass-savanna and forest cover in tropical and temperate basins, and mostly influenced by slope and shrub-grass-savanna cover in boreal basins. Our results highlight that in tropical and temperate basins, when not limited by water, partitioning tends to be equally distributed between E and R as forest cover increases. When shrub-grass cover increases, E dominates, indicating water limitations. In boreal basins the partitioning does not respond to forest cover, potentially due to the effects of snowmelt and geomorphology. Our results highlight that the effects of current changes in vegetation cover, including deforestation in the tropics, forest die-off in temperate regions and afforestation in boreal regions could expand into other societally-important processes, such as the regulation of river flow regimes.

KEYWORDS:
hydrological balance, basin attributes, correlations, patterns

1 | INTRODUCTION

Climate, basin physical attributes and land cover have been used as first order drivers of water balance partitioning (1, 2, 3). Streamflow (Q) production and evaporation (E) —the main components of long-term water balance partitioning— depend directly on precipitation (P), and are influenced by other atmospheric and surface attributes that include energy balance partitioning, surface albedo and roughness, soil properties, topography, basin area and vegetation cover (4, 5).

These attributes affect water balance partitioning through surface-atmosphere interaction via E, energy exchange and atmospheric circulation (6), surface and sub-surface processes that relate to water retention and infiltration (7), drainage capacity (8), hydrological time response and water distribution in time (9). Vegetation affects the dynamics of the global water cycle via its influence in atmospheric circulation (6, 10) leading to climate

† Ecohydrological effects on long-term water balance partitioning

patterns that determine regional- to continental-scale distribution of P (11, 12). Not only vegetation influences surface-atmosphere interactions, but also has an effect on the distribution of surface-subsurface partitioning of the water balance (13). The effect of these physical and ecological drivers of hydrological partitioning have been generally described in local- to landscape- and short-term scales. A critical challenge on integrating the mechanisms that affect hydrological partitioning is a global differentiation of the role of these physical and ecological drivers (14, 15).

A simple approach to relate long-term water balance partitioning with physical and ecological attributes can use a globally-applicable, robust and scale-independent indicator of surface hydrological regulation (16) based on runoff (R), similar to that proposed by (17) for E:

$$k = R/P. \tag{1}$$

This runoff ratio (k) —also known as runoff coefficient (18)— synthesizes the relationship between climatic forcing (indicated by P) and its conversion into surface hydrological fluxes (including both surface and subsurface processes, reflected on R). This approach uses R as a global hydrological indicator as it is widely and more directly measurable than E (19). Overall, in a given basin, higher values of k (which are always between 0 and 1, due to mass conservation) reflect greater efficiency in rainfall conversion to runoff. k values close to 1 imply that almost all the input (P) is converted into R, decreasing the amount of water transferred to the atmosphere through E (corresponding to the energy-limited region in the Budyko curve). The other extreme case is when k approaches a value of 0, where almost all P in the basin is converted into E, decreasing the amount of surface water represented by R (corresponding to the water-limited region in the Budyko curve). Although both E and R are directly correlated with P inputs, they are also controlled by vegetation and other physical attributes (20, 5). Consequently, the hydrological effects of these factors should be reflected in the behavior of k.

Here we calculate k for 126 independent and free-flowing river basins distributed among three major regions of the world: tropical, temperate and boreal. We further relate water balance partitioning with key physical and ecological attributes that include geomorphology, soils and land cover; and highlight how the major attributes that drive water balance partitioning (indicated by k) vary among regions and respond directly to global change effects.

2 | METHODS

2.1 | Data sources

We defined a 12-year study period (2001–2012) based on the availability of land cover data (MODIS-MCD12C1; (21); 500-m resolution maps). We selected basins located in a spatial domain between 60°N and 60°S to concentrate on basins where rainfall-runoff processes dominate the production of streamflow. We used digital elevation models (DEMs) extracted from the grid sources GTOPO30 (22) and SRTM (23) to delimit basin drainage areas. We selected basins with areas greater than 10,000 km^2 to guarantee that each basin covers a sufficient number of pixels to produce reliable estimations of precipitation, evaporation and land cover.

Our basins sample includes a wide range of ecological, climatic and hydrological characteristics; including different river basin sizes, land cover types, rainfall regimes and runoff patterns (Figs. 1 and 2). Because of this variability, we classified them in three major regions: tropical (0°–30°), temperate (30°–45°), and boreal (45°–60°). We used rainfall data for the same study period from the Tropical Rainfall Measuring Mission (TRMM-3B42) (24) for evaluations in tropical basins and the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis (25) for temperate and boreal basins. We used potential evaporation data from Global Land Evaporation Amsterdam Model (GLEAM version 2.0; (26)) for the same time period.

We used national and international streamflow databases (Supplementary Table S1), which are generally more limited in resolution and temporal coverage. To account for these limitations, we included natural streamflow records that covered at least 9 years in the same 12-year period. We selected free-flowing river basins with absence of major dams. The free-flowing river basins used are summarized in Supplementary Table S2. For boreal basins (specifically Mackenzie, Lena, Vitim and multiple basins in Canada), we used data for only 6 months per year (May to October) to include biologically active vegetation and streamflow dominated by rainfall-runoff processes. For comparison with other regions of the world, we included only the effects of rainfall by subtracting snow equivalent (from ERA-Interim reanalysis) from total precipitation. However, we acknowledge that streamflow in these regions is highly influenced by snow throughout the year via base flow.

To represent other basin physical attributes we calculated drainage area of each basin, mean slope (spatial average, from the DEMs), soil texture and soil types (based on (27)), and mean values (spatial average) of 7 soil quality indexes (based on Soil Quality of the Harmonized World Soil Database V1.2; (28)).

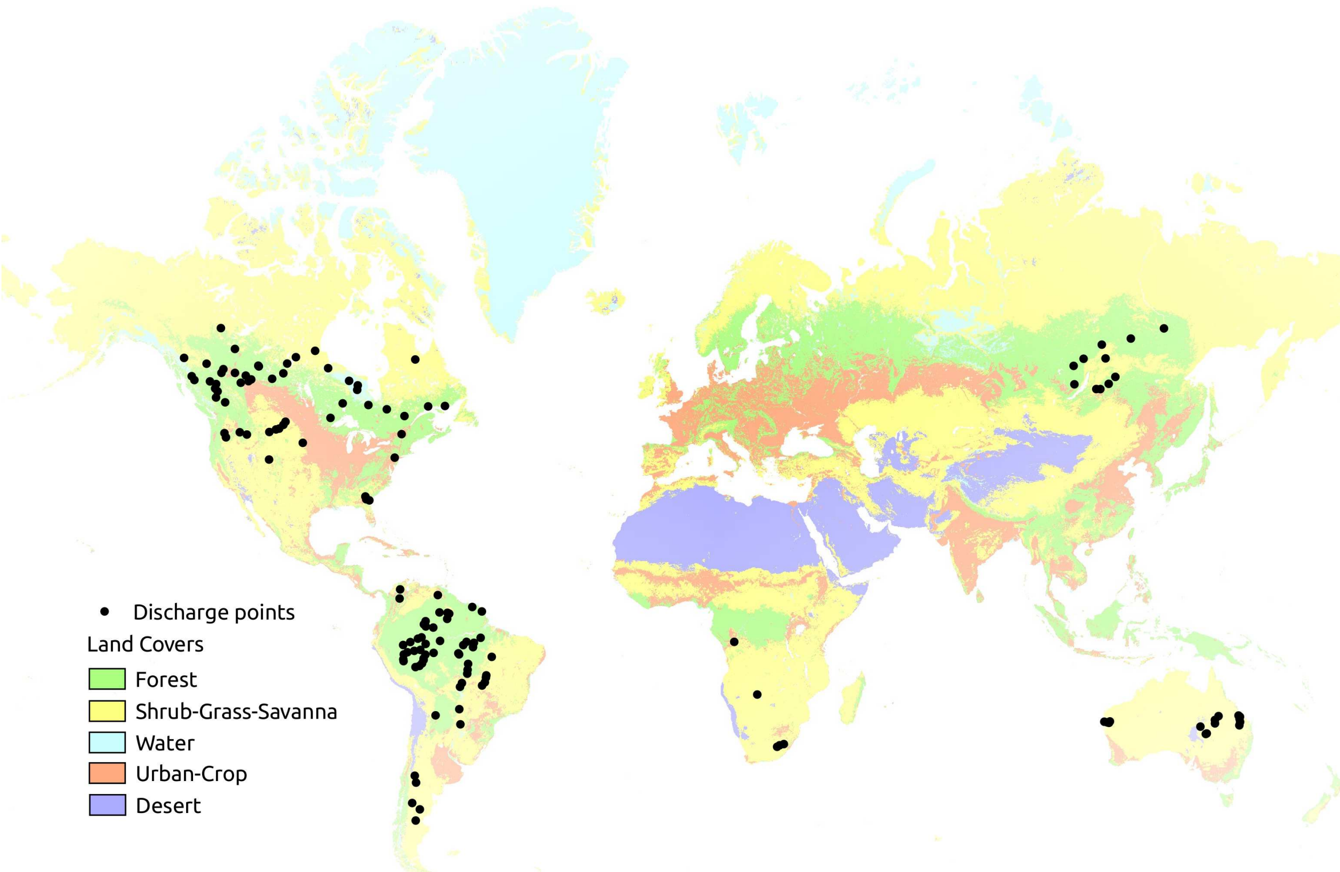

FIGURE 1 126 large river basins (greater than $10000km^2$) selected for our analysis and associated global reclassified map of land cover mode (the most frequent class between 2001-2012). Long-term water balance partitioning ($K = R/P$) was calculated for each basin.

2.2 | MODIS mode map

We defined a land cover map for each basin by selecting the temporal mode (the most frequent class) for each pixel using the 12-year map series (2001–2012, Fig. 1). Land cover classification was defined according to the International Geosphere Biosphere Programme (IGBP) scheme, which divides global land covers into 16 classes. We further grouped them into five classes: Forest includes evergreen and deciduous forest types; Shrub-Grass-Savanna includes two types of shrublands (open and closed), two types of savannas (woody and not) and grasslands; Urban-Crop includes croplands, urban zones and cropland/natural mosaics; Water includes open water areas, wetlands and snow; and Desert includes barren areas.

2.3 | k = R/P

We estimated cumulative runoff by dividing long-term (2001–2012) mean streamflow by drainage area in all 126 basins. We obtained each drainage area (always greater than 10,000 km^2) from the DEM of each basin, using the best watershed delineation generated in hydrological modules of GRASS GIS (http://grass.osgeo.org/). The delimited areas were compared with the reported areas in the outlet measurements of each basin and with available projects such as HydroSHEDS (http://hydrosheds.cr.usgs.gov/index.php) and SO-HYBAM project ((29); www.ore-hybam.org). Measurement errors of up to 10% were accepted. In cases where errors were greater than 10%, drainage areas were corrected until errors were reduced. Finally, we estimated rainfall as the spatial average of 12-year mean rainfall in all pixels in each basin.

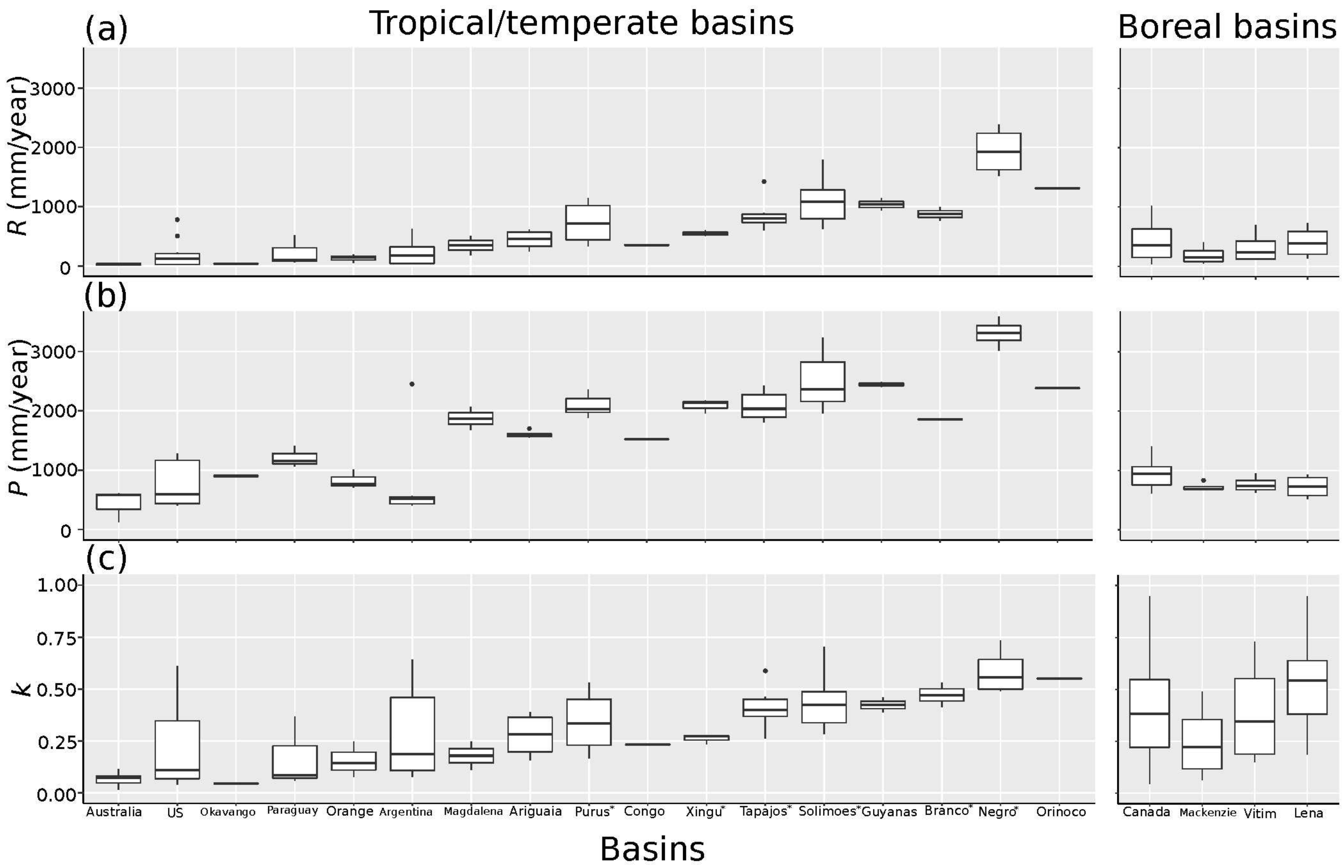

FIGURE 2 General global water partitioning ($k = R/P$) in 21 regions which include the 126 basins. Distribution of spatially averaged long-term runoff (a), rainfall (b) and k (c) for the 2001-2012 study period. * are basins contained in the Amazon

2.4 | Fixing autocorrelation

We removed autocorrelation problem commonly reported in nested basin studies by using Eq. (2) that creates independent basins for statistical analysis.

$$Vind[i] = \frac{V[i] * A[i] - V[i-1] * A[i-1]}{A[i] - A[i-1]}, \quad A[i] > A[i-1], \tag{2}$$

where $Vind$ is the resulting independent data for each variable; V is the autocorrelated variable (runoff, precipitation, land cover and physical attributes); A is the area of the basin; and i represents the target basin which contains the $i-1$ nested basin. This was applied to all nested basins, except in two rivers in Australia: the Barcoo river nested in the Cooper; and the Mackenzie river nested in the Fitzroy. When applying this procedure, resulting runoff values were negative due to large evaporative losses, suggesting that in these water-limited basins streamflow in a downstream basin cannot be isolated from streamflow produced in upstream basins.

2.5 | Physical and ecological attributes - k statistical analysis

To assess whether k-value was related to land cover and basin physical attributes, we implemented a series of correlation analyses. Land cover type was determined from the MODIS mode map using three general categories: (i) Forest, (ii) Shrub-Grass-Savanna, and (iii) Urban-Crop. The fraction of each land cover category was calculated for each basin as the number of pixels on each cover type divided by the total number of pixels in the basin. Finally, we calculated correlation coefficients (using PearsonâĂŹs, SpearmanâĂŹs and KendallâĂŹs correlation methods) between k-value and the fraction of all land cover types, as well as with the physical attributes of the basins (drainage area, slope, soil texture, soil type, and soil indexes). We used three correlation coefficients looking for more robust and resistant methods, in which case, the commonly used Pearson method is not recommended. Results were generally consistent among all methods. We fitted locally weighted polynomial regressions (LOESS) between

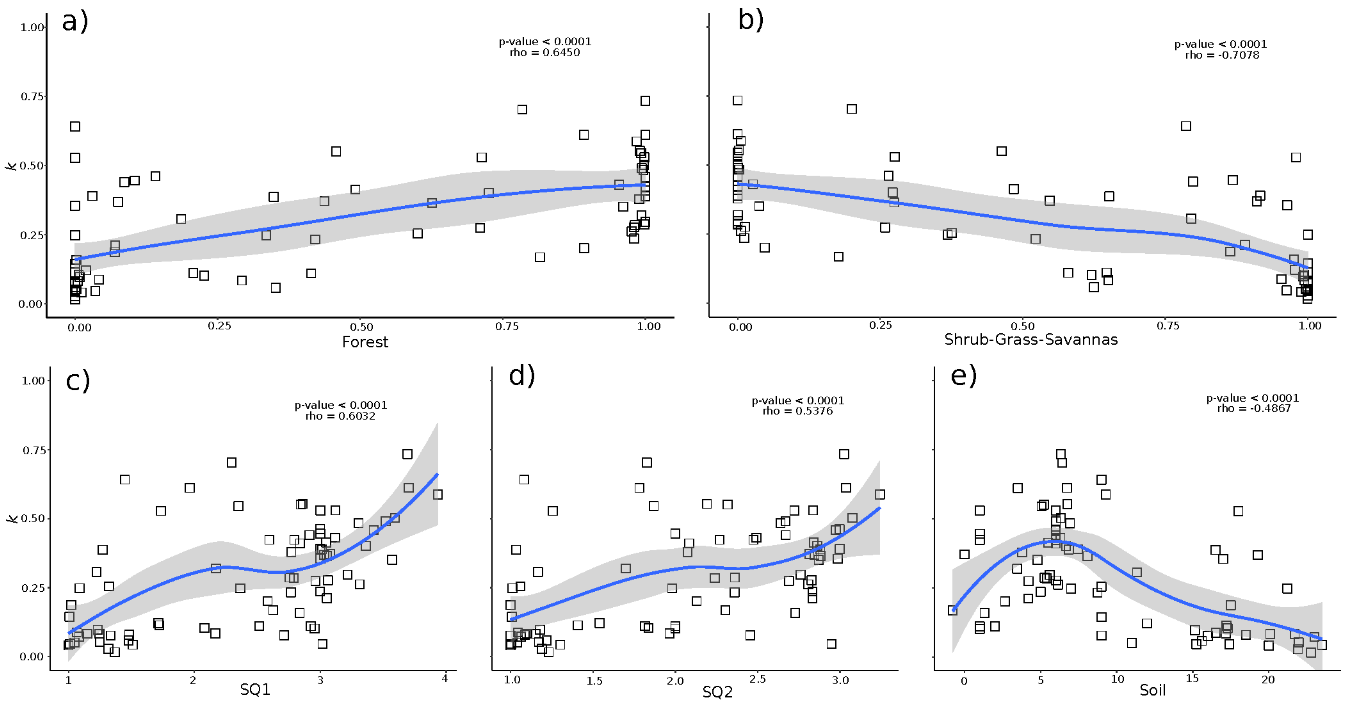

FIGURE 3 Water balance partitioning ($k = R/P$) in tropical and temperate basins as a function of: (a) Forest fraction, (b) Shrub-Grass-Savannas fraction, (c) SQ1 (nutrient availability), (d) SQ2 (nutrient retention capacity) and (e) soil type. The figure only shows the physical and ecological properties significant correlated with k. Spearman's correlation coefficients (rho) and p-values (indicating significance of the correlation) are highlighted in each case. Spearman's correlation was selected as a more robust an resistant method than Pearson's. Other correlations are presented in Supplementary Table S3. We fitted local polynomial regressions (loess, blue lines) and their 95% confidence intervals (grey).

significantly correlated physical/ecological attributes and k-values. Differences between the values of k and the possible theoretical values of k (ranging between 0 and 1) were evaluated (at α-level of 0.05) in all 126 basins using a one sample Wilcoxon-Mann-Whitney test (two-tailed method).

3 | RESULTS: DRIVERS OF HYDROLOGICAL PARTITIONING

In general, k is more variable in boreal than in temperate/tropical basins, even when P and R are not (Fig. 2). In tropical and temperate basins k values tend to be concentrated around two intervals: 0.1-0.2 and 0.4-0.5, apparently associated with rainfall amounts (Fig. 2 ; Wilcoxon-Mann-Whitney test; p-values $>$0.05), whereas in boreal basins k values concentrate in a single- larger interval between 0-2 and 0.4 (Wilcoxon-Mann-Whitney test; p-values $>$0.05). The highest values of k occurred in boreal basins while the lowest occurred in basins with the lowest precipitation values (Fig. 2).

3.1 | Tropical and temperate basins

k-value correlates positively with forest cover ($rho = 0.64; p =< 0.0001$; Fig. 3 a) while other types of vegetation cover, particularly Shrub-Grass-Savannas, correlate negatively with k (rho = -0.70; p = <0.0001; Fig. 3 b). These statistical results are consistent among multiple correlation tests (Supplementary Table S3). The sign and magnitude of the correlations suggest that there are fundamental differences between forests and other land cover types in terms of hydrological partitioning. These differences relate to the processes that govern long-term rainfall-runoff conversion (as indicated by k).

Along with vegetation cover, the other physical attributes that correlate with the behavior of k are (1) soil type (rho = -0.48, p=<0.0001; Fig. 3 c), a qualitative variable that represents the great world soil groups classification (30, 31) (the magnitude of the correlation is valid but the negative sign is not), which is partially defined according to land cover, and particularly the presence of forest (as an element of the five main dominant factors to develop a soil); and (2) two soil indexes related with nutrient availability and nutrient retention capacity (SQ1, with rho = 0.60, p=<0.0001 and SQ2, rho=0.54, p=<0.0001; Fig. 3 d-e), only soil texture is a common variable in the calculation of these two quality indexes (more details in (28)),

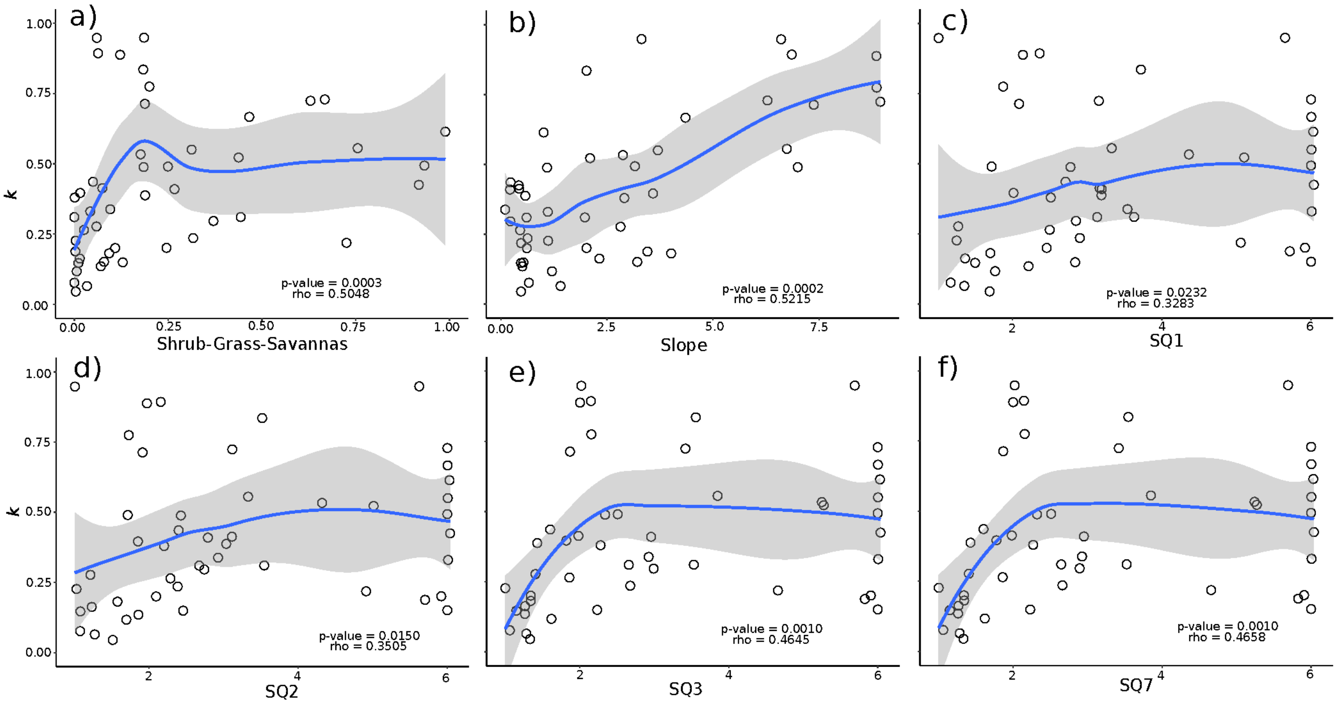

FIGURE 4 Water balance partitioning ($k = R/P$) in basins located in boreal regions as a function of: (a) Shrub-Grass-Savannas fraction, (b) mean slope, (c) SQ1 (nutrient availability), (d) SQ2 (nutrient retention capacity), (e) SQ3 (rooting condition) and (f) SQ7 (workability). The figure only shows the physical and ecological properties significant correlated with k. Spearman's correlation coefficients (rho) and p-values (indicating significance of the correlation) are highlighted in each case. Spearman's correlation was selected as a more robust an resistant method than Pearson's. Other correlations are presented in Supplementary Table S3. We fitted local polynomial regressions (loess, blue lines) and their 95% confidence intervals (grey).

nevertheless soil texture is not significantly correlated with k. Soil is an essential factor that limits vegetation development, but it is unlikely to be the main factor determining surface water balance partitioning in these regions, as highlighted by the correlation coefficients, which are smaller than those that relate k with forest cover fraction.

In addition to assessing correlations between k and physical and ecological attributes, we evaluated the shape of the numerical function that described these relations. The weighted polynomial regression (LOESS) between k and forest cover exhibits a linear pattern (slope of the fitting linear regression is 1.36, supported by r-Pearson coefficient; 3 a). The behavior of k in Shrub-Grass-Savanna is similar but opposite to that of forests, as it represents their absence. In Figures 3 d,e, the shape of the numerical function that relates k with soil quality indexes differs significantly from a line.

In synthesis, these results suggest that vegetation cover is the variable that better relates to hydrological partitioning in tropical and temperate regions and the effect of soil properties, although significantly correlated do not follow a linear relation.

3.2 | Boreal basins

k-value correlates positively with Shrub-Grass-Savannas cover (rho = 0.50; p = 0.0003; Fig. 4 a) and slope (rho = 0.52; p = 0.0002; Fig. 4 b). Weaker correlations are also present between k and three of the seven soil quality indexes (SQ1, with rho = 0.33, p = 0.0232; SQ2, rho = 0.36, p = 0.0150; SQ3, rho = 0.46, p = 0.0010; SQ7, rho = 0.47, p = 0.0010; Fig. 4 c-f). These statistical results are consistent among multiple correlation tests (Supplementary Table S4).

We analyzed the shape of the numerical function (LOESS) that described the relation between k and physical and ecological attributes correlated with it. Shrub-Grass-Savanna cover produces increases in k up until an approximate value of 0.25 in cover fraction. At this point, further increases in cover do not produce a significant increase in k (Fig. 4 a). The weighted polynomial regression (LOESS) indicates that k and slope are approximately linearly related (Fig. 4 b).

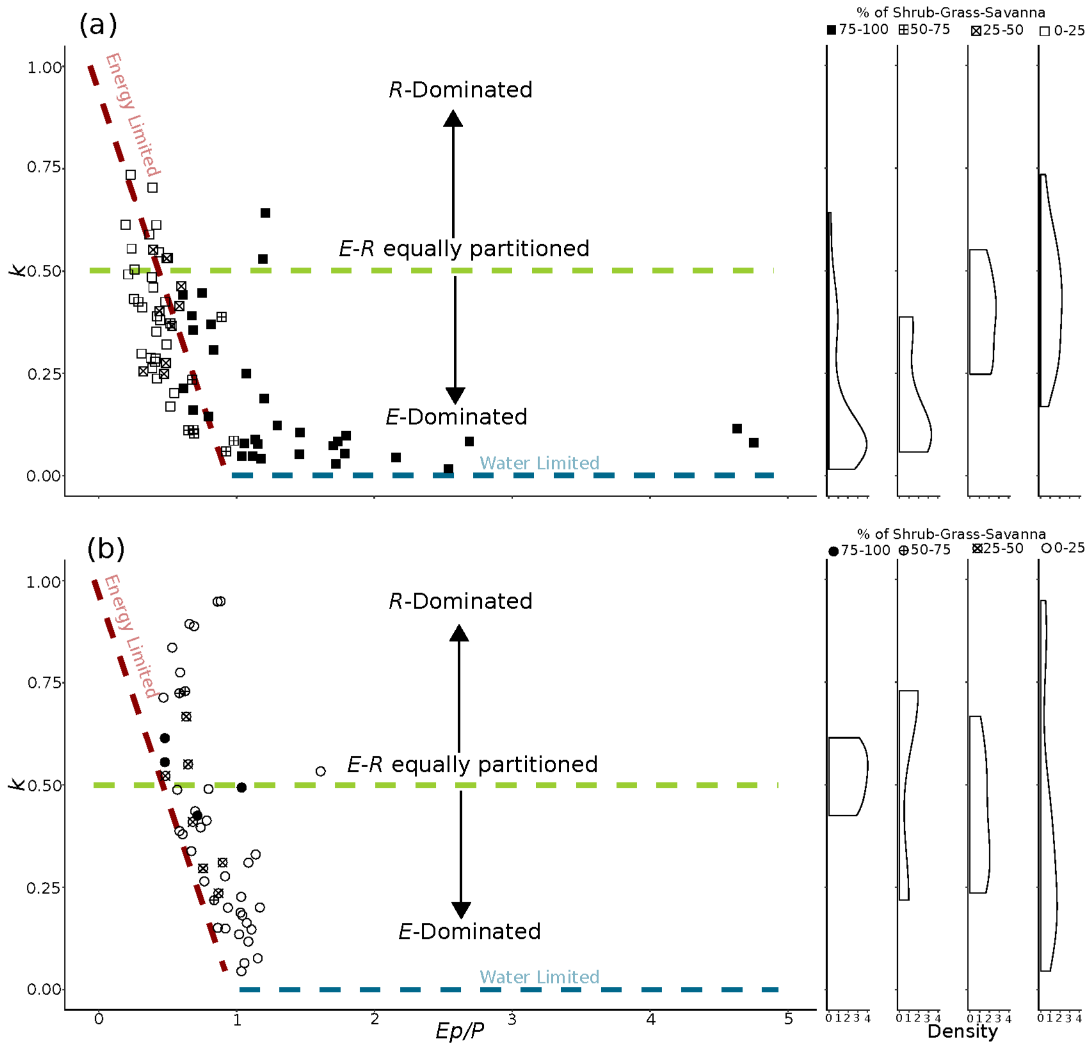

FIGURE 5 Budyko-like global classification of basins according to runoff production for (a) tropical and temperate basins and (b) boreal basins. E-dominated represents the water limited basins on tropical and temperate regions. In E-R equally partitioned basins forest cover is high (tropical/temperate regions), and surface water availability and atmosphere supply is guaranteed at the same time. In R-dominated basins (mostly contained in boreal regions) most water is contained in the surface compromising atmospheric moisture.

4 | DISCUSSION

In our analysis of 126 river basins in three major regions of the world (tropical, temperate and boreal), we use k index as a descriptor of hydrological partitioning. By analyzing the behavior of k along with related physical and ecological attributes, we differentiate the relative importance of R and E in long-term hydrological partitioning. In general, low values of k can occur when R is much smaller than P, independent of their magnitude. For example, although different in P, Australia, Paraguay and US basins have similar low values of k due to their relatively low values of R (Fig. 2). This can be interpreted as low efficiency in the conversion of rainfall into runoff, and potentially higher importance of E in hydrological partitioning (Fig. 5). In contrast, a high value of k indicates high efficiency in the conversion of rainfall into runoff. This is the case, for example, of the forested basins in the Amazon (Negro, Branco and Solimoes), some basins in Canada and the Lena river basin in Russia. In these cases, R values are closer to P, which leads to a more R-dominated hydrological partitioning (Fig. 5).

Vegetation cover, indicated by the amount of forest and Shrub-Grass-Savanna in all basins is related to k (Fig. 3 and Fig. 4). Not only vegetation cover relates to the magnitude of k but also potentially with its spatial variability, such that it tends to be reduced in basins dominated by one particular type of vegetation cover and increases when a more mixed mosaic of cover types dominates the basin (Fig. 1). For example, the more forested basins of the Amazon and the Shrub-Grass-Savanna dominated basins in Australia have lower spatial variability of k while the temperate basins in US and Argentina, with highly variable k-values, have intermediate values of forest and Shrub-Grass-Savanna. This is likely related to variations in potential evaporation and precipitation ratios inside basins in these regions.

By using k in combination with the potential behavior of E, we propose a framework that describes the main attributes conditioning the production of streamflow. Our framework also shows how these attributes interact with the factors influencing E, to produce long-term patterns of E-R partitioning. Our results show that tropical and temperate basins with low k values, where hydrological partitioning tends to be dominated by E, are water-limited according to the Budyko theory for evaporation (17) and tend to be dominated by Shrub-Grass-Savanna vegetation cover (Fig. 5 a). In these regions k values converge towards a mean value around 0.5 (E-R equally partitioned) when Shrub-Grass-Savanna cover is low (0-25%) and forest cover is high. Boreal basins that are generally energy-limited exhibit values of k scattered along all the entire range of values (0-1), and the behavior of k does not relate directly with the amount of forest cover (Fig. 5 b). This is consistent with the idea that for these regions, rainfall-runoff processes are not the main drivers of streamflow dynamics (32). More specifically, in E-dominated basins (water-limited) on tropical and temperate regions, most water is returned to the atmosphere compromising plant productivity and surface water availability (33), potentially limiting the occurrence of forests (34). In contrast, in E-R equally partitioned basins (close to green line in Fig 5 a), where forest cover is high, surface water availability and atmosphere supply is guaranteed at the same time, suggesting a potential optimization of hydrological partitioning. Our results show that vegetation cover type is more related to k than other physical attributes associated with hydrological partitioning.

Forest cover can regulate hydrology through multiple mechanisms. The capacity of forests to maintain a streamflow regime via regulation of surface and subsurface moisture has been widely documented (35, 36, 37, 38, 15, 39). Further, the presence of continuous forests in large basins can induce cloud formation processes via evaporation and atmospheric instability that triggers convective transport of moisture (40, 41). More generally, the effects of forests in rainfall and its conversion into other hydrological fluxes is associated with a suite of ecological attributes (15). These attributes include, for instance, stomatal control of evaporation (42), physiological adaptations for water and light use efficiency (43), soil moisture control via canopy effects on hydrological partitioning (44), canopy effects on atmospheric moisture dynamics and presence of cloud condensation nuclei (45). Along with vegetation, soils also play a key role on the dynamics of hydrological partitioning (as highlighted in Fig. 3) through multiple mechanisms including: infiltration capacity that affects surface and sub-surface distribution of water (46); moisture retention capacity is a key ecosystem supporting soil property (34); soils favor plant development through biogeochemical dynamics and nutrient supply (47).

k reaches higher values in boreal regions than in tropical/temperate regions (more than 30% of k values are greater than 0.5 in boreal basins compared to less than 10% of k values between 0.5-0.75 and no values higher than 0.75 in the tropical/temperate basins). The basins with high k values (some of them close to 1) correspond to R-dominated basins (Fig. 5 b), i.e. most water remains in the surface compromising atmospheric moisture. The high values of k in these basins are related with the common energy limitations in these regions, reducing the rates of E (Budyko curve in Fig. 5 b). Although we subtract snow-melt equivalent from streamflow, snowmelt processes significantly affect base flow in these basins (32, 48, 49). In this region, the presence of forest cover seems to be less important than Shrub-Grass-Savanna cover as a driver of long term hydrological partitioning. A combination of physical and ecological attributes that potentially relate to snow-dominated streamflow production explain this partitioning pattern. These attributes include slope (50, 51), Shrub-Grass-Savanna cover (52) and, to a lesser extent, properties that relate to the general biochemical conditions of the soil (53). Most basins, either tropical, temperate or boreal, are energy-limited and E-dominated (basins close to red line with k-values above 0.5 in Figure 5) Although these energy-limited basins are affected by climatic conditions that reduce potential evaporation (54, 55), they are E-dominated basins unable of retain water in surface. This is likely the response to the absence of forest in tropical/temperate regions (>75% of Shrub-Grass-Savannas fraction, in Fig. 5) and the presence of forest in some boreal regions (<25% of Shrub-Grass-Savannas fraction, in Fig. 5).

Water-limited basins are mainly tropical/temperate, with predominant (>75%) Shrub-Grass-Savanna (56). A predominance of this kind of vegetation generally indicates high energy availability and the absence of ecological and physical mechanisms to retain water in surface, affecting the portion of P that is potentially converted into R (56). Boreal basins are generally not water-limited, due to the climatic conditions and related low potential evaporation (32, 48, 49).

Overall, partitioning in all regions is generally dominated by E, with two main exceptions: (1) largely forested (> 50-75, last two distributions in Fig. 5a) tropical/temperate basins and, (2) boreal basins mostly covered by Shrub-Grass-Savanna. These two cases describe a close to optimum production of R that corresponds to approximately half of the amount P (leaving the other half to E). This behavior is generally explained by the role of ecosystems, particularly forests, in tropical and temperate regions. However, in boreal basins, other processes related to the interaction of geomorphological attributes and snowmelt dynamics may play a more significant role in the regulation of hydrological partitioning. Our results indicate that the potential effects of Shrub-Grass-Savanna encroachment is latitude-dependent, with opposite effects on boreal vs. tropical/temperate basins.

In synthesis, we use robust data (only free-flowing rivers were used and the autocorrelation issue in nested basins was corrected) to produce a simple global indicator of hydrological behavior that relates hydrological partitioning with ecological and physical attributes of a basin. Our global analysis shows that vegetation cover plays a fundamental role in the partitioning of the water balance. In particular, the amount of forest cover and associated soil properties relates to a more even partitioning of P into E and R in tropical and temperate basins. Loss of forest cover in these regions leads to a more E-dominated partitioning and is associated with water limitations, with important ecological, hydrological and biogeochemical implications (57, 58). Importantly, these forest effects are independent of basin area, topography, ecosystem type and rainfall regime. In boreal regions, however, the effects of vegetation cover and basin physical attributes relate more to the potential effects of snow on streamflow production, such that any change in these dynamics can have long-term effect on hydrological partitioning. Our results highlight that the consequences of current unprecedented rates of land cover changes and forest loss associated with global change processes could expand into other societally-important natural processes, such as large-scale hydrological regulation.

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Author contributions

D. Mercado-Bettín, JC Villegas and JF Salazar designed the research and wrote the manuscript; D. Mercado-Bettín performed data analysis.

Financial disclosure

None reported.

Conflict of interest

The authors declare no potential conflict of interests.

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Chapter 4

Streamflow changes due to climate and land cover changes in global river basins

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Manuscript in preparation.

Streamflow changes due to land cover changes in global river basins

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Key Points:

- Besides climate, land cover is a sensitive factor that could influence surface water availability.
- We separated changes of streamflow due to climate and land cover changes over time in 54 basins.
- We discuss that the method used require changes to account for all process relate to large basins.

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Abstract

Surface water availability is vitally important for any region in the world. It depends mainly on climate regimes as well as physical and ecological attributes of the river basins. Land cover is one of those attributes which is sensitive to continuous changes over time. To identify implications of land cover changes on water availability (here defined as streamflow), we analyzed the elasticity of streamflow due to both, climate changes and land cover changes, in 54 large "natural-flow" river basins ($> 10000 km^2$) with changes in the mean values of streamflow in a time window of at least 8 years. Following the method, we separated the changes of streamflow due to changes in climate from the changes of streamflow due to changes in land cover. We compared the resulting streamflow changes due to land cover changes, with independent data of changes in the fraction of land cover of each basin in the same time period. We found that in most of the studied basins in the Amazon and in all of the basins inside the Paraguay river, a reduction of streamflow over time match with a decrease in forest fraction and increase in cropland and/or grassland covers. Different land cover changes mixes match with increasing and decreasing streamflow in US and Canada basins. Additionally, 24 of all the basin studied have a absence of land cover changes, i.e, the streamflow changes over time mainly depends on climate changes. Our results contribute to the current debate about the effects of land cover on surface water availability and its relation with atmospheric-surface water exchanges in large areas.

1 Introduction

Streamflow changes along time depend mainly on changes in climate and attributes of the basin [*Zhou et al.*, 2015]. Accordingly, precipitation and potential evaporation are the widely-known variables representing these changes in streamflow [*Budyko*, 1974]. Nevertheless, there are other physical and ecological attributes also affecting these streamflow changes. Among these, land cover is a sensitive attribute to changes in a short-to-long time scales [*Mahmood et al.*, 2014; *Foley et al.*, 2005; *Sterling et al.*, 2013; *Bonan*, 2008].

Land cover changes have been associated with hydrological implications in many studies [*Bruijnzeel*, 2004; *Foley et al.*, 2005; *Sun et al.*, 2006; *Spera et al.*, 2016; *Farley et al.*, 2005; *Twine et al.*, 2004; *Bosch and Hewlett*, 1982; *Costa et al.*, 2003; *Wagner et al.*, 2016]. These implications, which are reflected in streamflow changes over time, depend on the spatial scale of the studies [*Zhang et al.*, 2016; *Wagner et al.*, 2013]. There is no consensus among the studies evaluating the effects of land cover changes on the direction of the changes in water availability [*Montanari et al.*, 2013; *Andréassian*, 2004; *Ellison et al.*, 2012; *Fohrer et al.*, 2005].

There are many paired-catchment studies analyzing local and short-term streamflow changes due to land cover changes [*Brown et al.*, 2005; *Bosch and Hewlett*, 1982; *Twine et al.*, 2004]. Moreover, some studies analyze changes of hydrological and climate variables over time in specific regions under ongoing land use changes [*Sun et al.*, 2006; *Costa et al.*, 2003]. But global analyses that relate land cover changes to changes in streamflow are less common [*Zhou et al.*, 2015]. Particularly, large regions experiencing important land cover changes processes such as deforestation (e.g. the Amazon, *Werth and Avissar* [2002]) and afforestation (e.g. China, *Huang et al.* [2003]), requires studies evaluating the effects of these developments on water availability.

Due to the climate variability associated with particular atmospheric conditions in each region of the world [*Karl and Trenberth*, 2003], the quality of land cover information over time in a global scale [*Congalton et al.*, 2014] and the influence of human (e.g dams and reservoirs) over basin drainage [*Haddeland et al.*, 2014], the exercise of separate streamflow changes due to both climate and land cover changes is complex. However, under the current and constant climate changes and human intervention all over the world, there is an urgent need to relate both changes and the streamflow changes in large basins. In this study, we show a general description of the quantitative changes of river flows depending on these two variables, using a traditional method.

2 Methods

2.1 Data

We used precipitation (P) data from the Multi-Source Weighted-Ensemble Precipitation (MSWEP V1.1, 0.25°) between 1980-2012 and potential evaporation from the Global Land Evaporation Amsterdam Model (GLEAM version 2.0; *Miralles et al.* [2011]) for the same time range. From this data, we calculated the spatial average for each basin to obtain a time series of precipitation and evaporation.

We calculated streamflow (Q) from discharge data and the drainage area (A, calculated from Digital Elevation Model (DEM)) of each basin. Q is the result of dividing the annual discharge by A on each basin (the resulting Q is in water level units (mm); Q in this case is also refereed as runoff). Discharge data were obtained from multiple national water databases, Observation Service SO HYBAM and Global Runoff Data Center (GRDC) (Supplementary Table S1). The time range in this study is irregular because the time series used for each basins depends on the availability of discharge data. We allowed up to 3 years (approximately 10% of the mean number of year for all basins (30 years)) of missing data for all basins. The years with less than 9 months of available data were regarded as missing data. Then, missing data in the time series of streamflow were interpolated using the Weighted Moving Average method (taking the two previous and the two following years into account). The time range in the other climate and land cover variables were adjusted in each basin according to this availability.

We used historic land cover data from the Land-Use Harmonization (LUH2 v2h, *Hurtt et al.* [2011]) project. We reclassified (Table 1) the land cover according to ORCHIDEE Data Assimilation Systems (ESA CCI LAND COVER/Cross-Walking Tables (CWT)). We calculated the time series of the fraction (percentage) for all land cover types for each basin, according to the spatial average from the pixels of each land cover contained on each basin.

Table 1. Land cover reclassification

Original classification based on LUH2 v2h	**Reclassification based on ORCHIDEE**
Forested primary land Potentially forested secondary land	Forest
Non-forested primary land Potentially non-forested primary land Managed pastures Rangeland	Grass/Bare Soil
Urban land	Urban
c3ann c4ann c3per c4per c3nfx	Cropland

2.2 Elasticity to calculate changes in P and Ep

A traditional method to represent changes in streamflow due to changes in climate variables and land cover is reflected in Eq. 1 [*Zheng et al.*, 2009].

$$\Delta Q = \Delta Q_c + \Delta Q_l \tag{1}$$

with:

$$\Delta Q_c = \Delta Q_P + \Delta Q_{Eo} \tag{2}$$

Where P represents precipitation, Eo represents potential evaporation, ΔQ_c represents changes in streamflow due to climate changes, ΔQ_l represents changes in streamflow due to land cover changes, ΔQ_p represents changes in streamflow due to precipitation and $\Delta Q_E o$ represents changes in streamflow due to potential evaporation. Assuming that land cover changes are independent of climate (currently, land cover/land use changes are related to human decisions *Vitousek et al.* [1997]; *Wagener et al.* [2010]), we can obtain the changes in streamflow due to land cover changes subtracting the streamflow changes due to climate changes.

Among the methods to calculated streamflow changes due to climate changes over time (ΔQc), we selected the elasticity (ϵ) method [*Schaake et al.*, 1990; *Dooge*, 1992]. The elasticity is defined as the rate of change of streamflow with respect to changes in precipitation (ϵ_P) and/or potential evaporation ($\epsilon_E o$). So that, Equation 2 can be rewritten as:

$$\Delta Q_c = \epsilon_P \frac{\Delta P}{\overline{P}} + \epsilon_{E_o} \frac{\Delta E_o}{\overline{E_o}} \tag{3}$$

We decided to used the non-parametric approaches proposed by *Zheng et al.* [2009] (Eq. 4) and *Sankarasubramanian et al.* [2001] (Eq. 5), and 4 parametric approaches based on the common Bukyko-like models [*Schreiber*, 1904; *Budyko*, 1971; *OlâĂŹDekop*, 1911; *Turc*, 1953; *Pike*, 1964] (Eq. 6-7) to calculate ϵ_P and ϵ_{Eo} due to these approaches have been tested in multiple regions around the world [*Yates and Strzepek*, 1998; *Chiew*, 2006; *Fu et al.*, 2007].

$$\epsilon = \rho_{X,Q} * C_Q / C_X \tag{4}$$

Where C_Q represents the coefficient of variation of Q and C_X represents the coefficient of variation of X. X represents P or E_o.

$$\epsilon = median(\frac{(Q_i - \overline{Q})\overline{X}}{(X_i - \overline{X})\overline{Q}}) \tag{5}$$

Where i represents each year in the time series.

$$\epsilon_P = 1 + \frac{\phi F'(\phi)}{1 - F(\phi)} \tag{6}$$

with,

$$1 = \epsilon_P + \epsilon_{Eo} \tag{7}$$

Where ϵ_P is the streamflow elasticity to precipitation and ϵ_{E_o} is the streamflow elasticity to potential evaporation; ϕ is the ratio E_o/P; F and F' are the function and derivative function of each Budyko-like model [*Arora*, 2002].

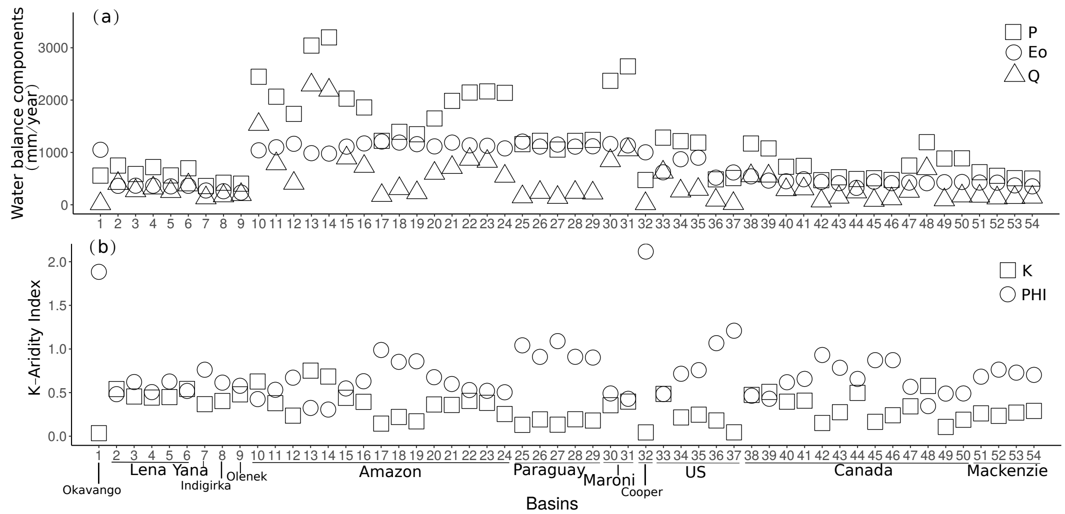

Figure 1. Mean values of P, R and E_o (a) and runoff coefficients (K) and aridity indexes (ϕ) (b) for the 54 basins selected with changes in mean values of streamflow over time.

We used the change-points test (*Taylor*, AMOC method, *Scott and Knott* [1974]) to identify the significant (penalty value = 0.05) year (point) which divides each time series in, two other time series with different means in streamflow. We selected a time windows of changes of 8 years. Accordingly, this limit of 8 years was selected according to the availability of large basins with significant long-term changes in streamflow (Supplementary Fig. S1). Accordingly, we can identify one point in each time series where the statistical properties (in our case the mean) of the observation (in our case streamflow data) change [*Killick and Eckley*, 2014].

3 Results: Changes in streamflow due to changes in land cover

We selected 54 basins (with basin areas greater than 10000 km^2) from a collected global discharge data (Supplementary Table S1), with changes in mean values (change-points method) of streamflow in a time window equal or greater than 8 years. These selected basins have different climate regimes, aridity indexes (ϕ) and runoff coefficients ($K = Q/P$) (Fig. 1). 19% of the basins are water-limited and 81% are energy-limited basins according to the aridity index ($\phi > 1$ and $\phi < 1$, respectively; Fig. 1b).

We calculated the elasticity of streamflow to precipitation and potential evaporation using the 6 methods mentioned above (Fig. 2, Supplementary Table S2) for each basin. According to the parametric methods (Fig. 2a), the elasticity of streamflow to climate change is higher in regions with higher aridity indexes [*Chiew*, 2006]. Therefore, streamflow in arid or semi-arid regions are more sensitive to changes in climate. In general, using the two non-parametric methods (Fig. 2b) the elasticity of streamflow to climate changes is also higher in regions with higher aridity indexes. However, the behavior of the elasticity is very irregular. Some basins with high aridity index have less elasticity than other basins with low aridity indexes, which is related to specific characteristics of climate variables in each region. The rate of changes in $\epsilon_E o$ with aridity index is greater than the rate of changes in ϵ_P, due to the fact that E_o has lower variance in all basins and higher mean values than P in the arid basins (in general, the coefficients of variation for E_o are lower than in P, the standard deviation values are 0.0120 and 0.0465, respectively). There are $\epsilon_E o$ with positive values, which is related to direct correlation coefficients (some of them non-significant, e.g. the two cases with posi-

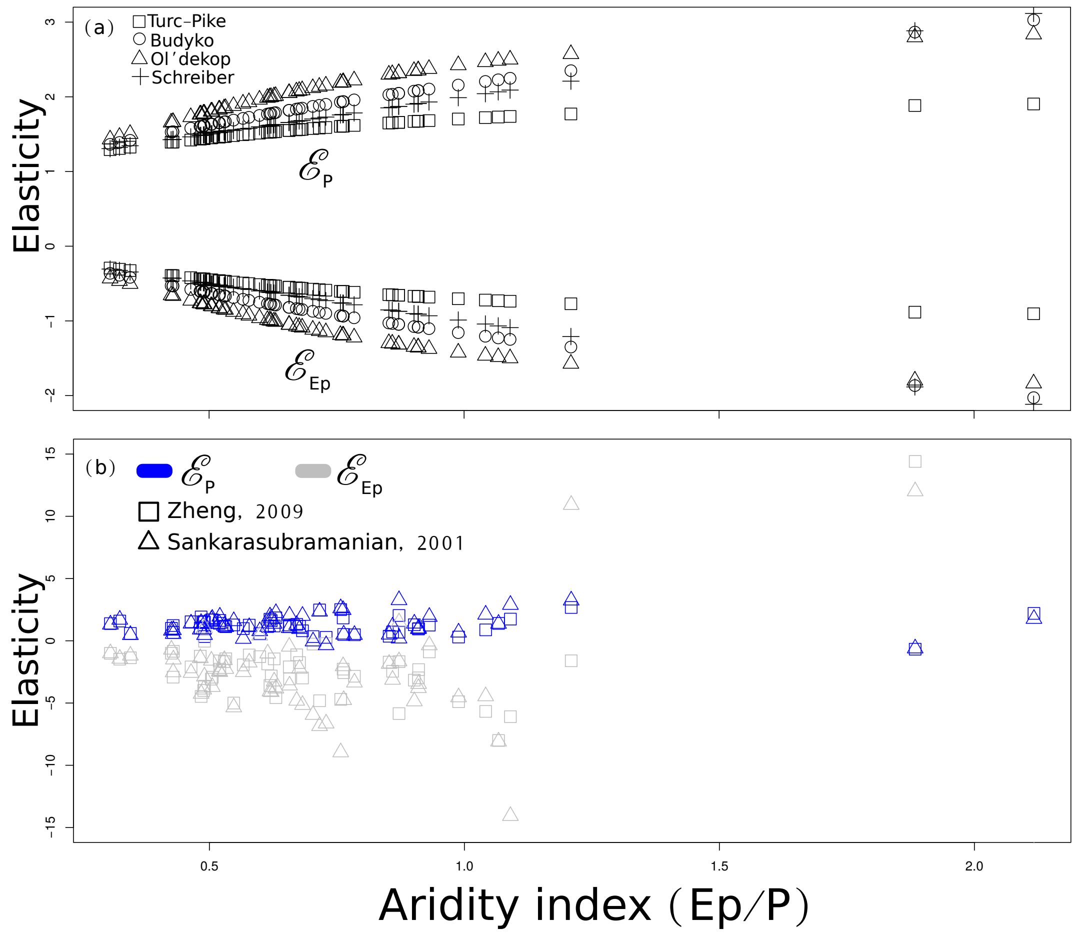

Figure 2. Elasticity calculated from 2 nonparametric methods (a) and 4 parametric methods (b) based on Budyko models.

tives values of ϵ_{Eo} have p-values>0.2) between E_o and Q. These elasticity values allow to analyze the climate influences in streamflow changes over time. In the following these are used to separate the changes of streamflow due to changes in climate from the changes of streamflow due to land cover changes.

Using the time series of precipitation and potential evaporation for each basin, we calculated the changes in streamflow due to changes in climate (ΔQ_c, Supplementary Tables S3) using the 6 elasticity methods. Then, we obtained the changes of streamflow due to changes in land cover (ΔQ_l) according to Eq. 1 (Fig. 3). We used the average values of ΔQ_c obtained from the 6 methods for each basin (blue circles, Fig. 3a) and ΔQ values (black squares) to calculate ΔQ_l values (green triangles). Finally, we obtained the changes of streamflow due to changes in climate and the changes of streamflow due to land cover changes.

Ongoing land cover and climate changes processes match with increasing and decreasing streamflow in the different river basins (Fig 4.): The Okavango basin (1, Fig. 4b) has a decrease in streamflow (Q); all the basins (2-9) located in Russia have an increase in Q; in the Amazon river, 8 basins (12, 17-20, 22-24, Fig. 4b) have a decrease in Q and 7 basins (10-11, 13-16, 21) have an increase in Q; all basins in the Paraguay river (25-29) have a decrease

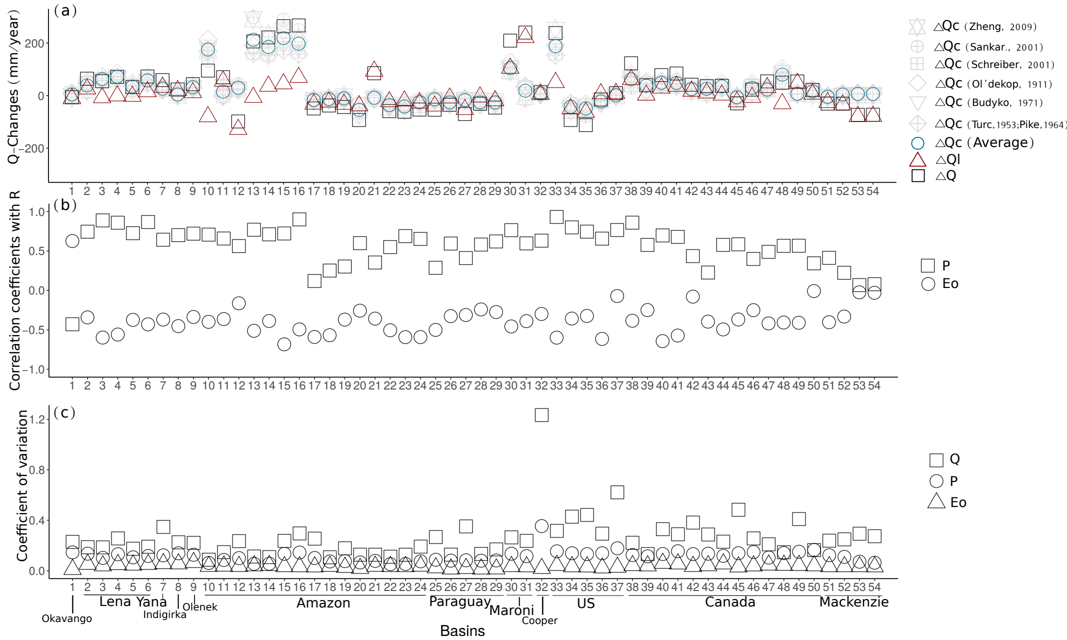

Figure 3. Changes in streamflow due to changes in climate and land cover (ΔQ, ΔQc and ΔQl) (a), Pearson's correlation coefficients between both P-Q and E_o-Q (b) and coefficients of variation for Q, P and E_o (c).

in Q; the basins (30-31) located in the Maroni river have an increase in Q; the basin (32) located in the Cooper-Thomson river has an increase in Q; in US basins, 3 basins (34-36) have an decrease in Q and 2 basins (33, 37) have an increase in Q; and in the basins located in Canada, 5 basins (45, 51-54) have a decrease in Q and 12 basins (39-44, 46-50) have an increase in Q.

The basins reflect particular behaviors (Fig. 3 and 4) of ΔQ_c, ΔQ_l (red arrows in Fig. 4c) and ΔQ (Blue arrows in Fig. 4c). There are 3 cases when ΔQ increase over time: ΔQ_c and ΔQ_l are both positive (24 cases); ΔQ_c is higher (big arrows in Fig. 4c) in magnitude than ΔQ_l and they are positive and negative, respectively (7 cases); and ΔQ_c is lower in magnitude than ΔQ_l and they are negative and positive, respectively (1 case). And there are also, 3 cases when ΔQ decrease over time: ΔQ_c and ΔQ_l are both negative (16 cases); ΔQ_c is lower (small arrows in Fig. 4c) in magnitude than ΔQ_l and they are positive and negative, respectively (5 cases); and ΔQ_c is higher in magnitude than ΔQ_l and they are negative and positive, respectively (1 case).

30 out of the 54 basins analyzed have changes in land cover over time that could affect streamflow (Fig. 5). We compared the changes in land cover types (Fig. 5a) with (i) the initial state of streamflow ($Q1$, red bar in Fig. 5b), (ii) the initial state of streamflow plus streamflow changes due to climate changes ($Q1 + \Delta Q_c$, green bar) and (iii) the initial state of streamflow plus streamflow changes due to climate changes plus streamflow changes due to land cover changes ($Q1 + \Delta Q_c + \Delta Q_l = Q2$, blue bar) on each basin. In general, in the Amazon basin there is an increase in both, cropland and/or grassland covers and a decrease in forest cover matching with decreasing (9 cases) and increasing Q (4 cases). In the Paraguay basin there is a decrease of forest cover and an increase in cropland cover, matching with a decreasing Q in all cases (5). The basins in the US have in general decreasing cropland cover and increasing grass, urban and/or forest covers, that match with increasing (3 cases) and

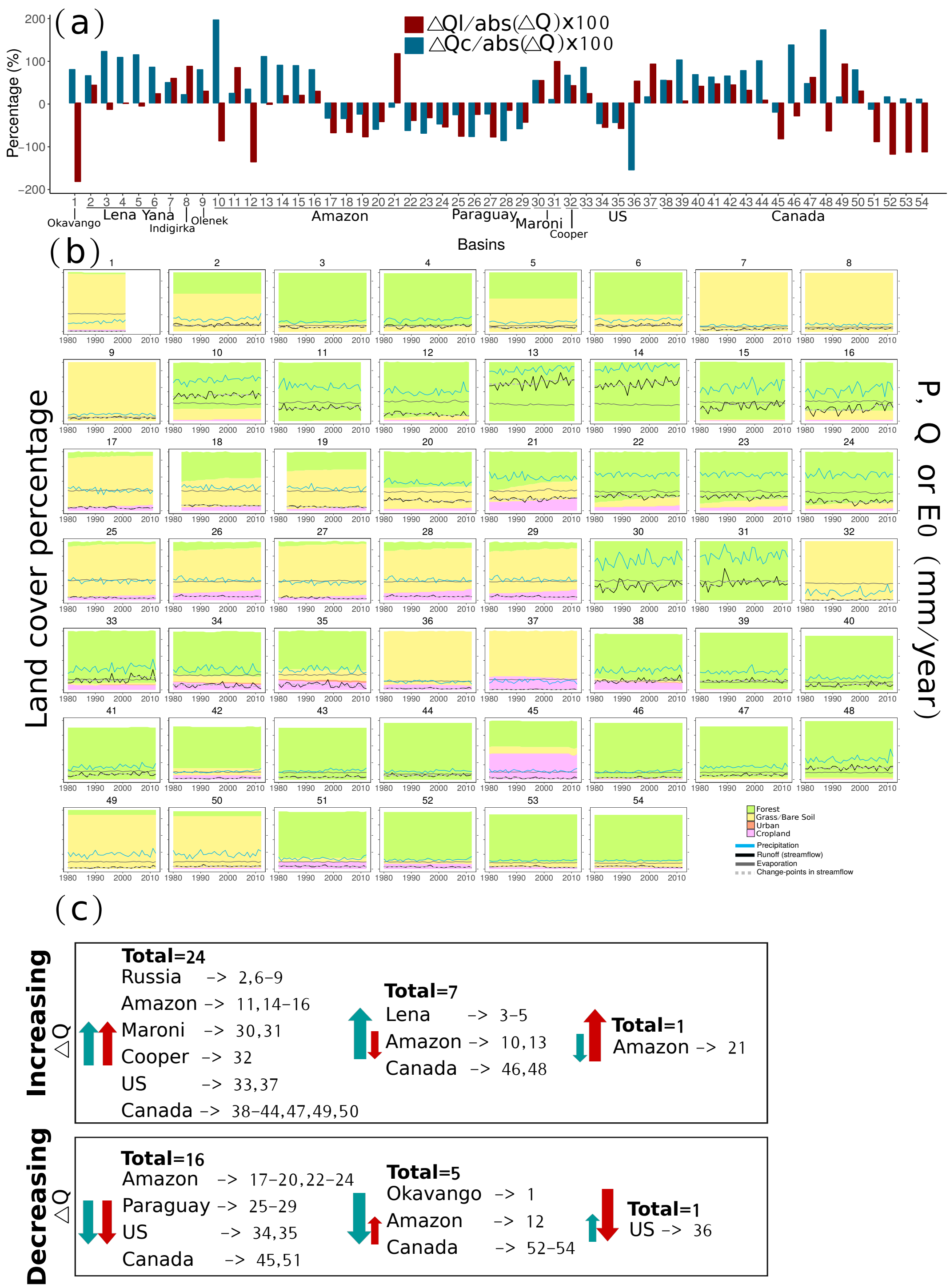

Figure 4. Percentage of changes of streamflow due to both changes in climate and land cover respect to total streamflow changes (a), time series of the hydrological and land cover variable for all 54 basins (b) and cases of increasing and decreasing ΔQ according to magnitude and direction of ΔQ_l and ΔQ_c (c). The big arrows represent higher magnitude of streamflow changes due to climate (blue arrow) or due to land cover (red arrow), the direction of the arrows represents whether they these changes are negative (down arrow) or positive (up arrow).

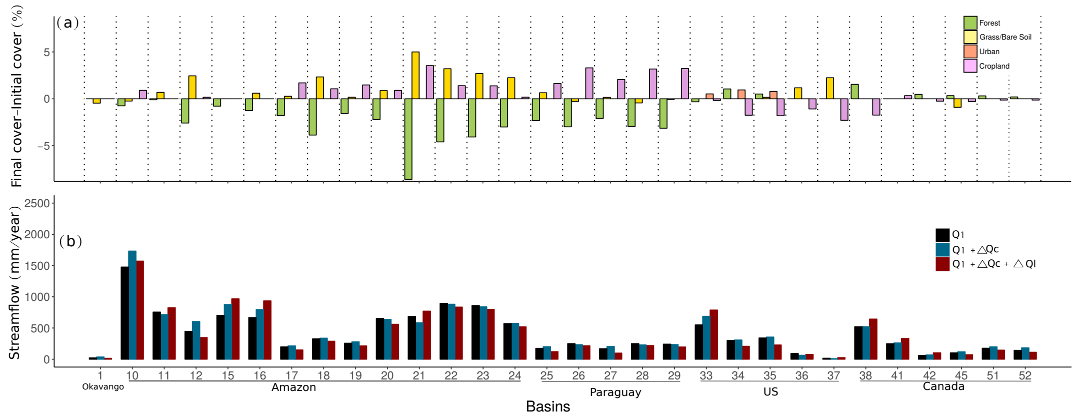

Figure 5. Percentages of land cover changes (a) and base streamflow (black bars) plus streamflow changes due to climate (blue bars) and plus streamflow changes due to land cover (red bars) (b)

decreasing Q (2 cases). The basins in Canada have different small land cover change arrangements between grass, cropland and forest covers, with increasing and decreasing Q cases among the basins. The Okavango basin has a decrease in Q that match with a decrease in grass cover. The study of each particular basin is beyond this research, rather is focused on analyze particular pattern among all basins.

To properly analyze the influences of land cover on Q, we related changes in streamflow due to both climate changes (ΔQ_c) and land cover changes (ΔQ_l), to each land cover type changes (Fig. 6). There are no significant correlations (congruent among the 3 method used: Pearson, Kendall and Spearman) between land cover changes and either ΔQ_c (Fig. 6a) or ΔQ_c (Fig. 6b). There is only significant correlation between grass cover and ΔQ_l when using Pearson correlation. Further, there is no clear general relation between changes in streamflow and changes in the different land cover types. These Q changes found can be the consequences of multiple land cover changes at the same time. For instance, most of the cases with a decrease in Q in the Amazon and Paraguay basins match with increasing cropland and decreasing forest cover at the same time, or some cases in the US basins show that a decreasing cropland and increasing forest cover match with an decreasing Q. In general, there is no particular relation among the land covers and the streamflow changes.

4 Discussion

The resulting effects on streamflow changes due to land cover changes are not associated with a particular land cover, rather are related to different arrangements between forest, grass, urban and crop covers. This is reflected in the absence of significant correlations (Fig. 6b) between each particular land cover and the changes of streamflow due to land cover changes (ΔQ_l). Accordingly, our results are useful to analyze, in general, the behavior of streamflow changes on each studied region depending on particular climate and land cover changes, instead of relate a single land cover with the general changes in streamflow in the entire sample.

Our results can exhibit different patterns in the same region representing the sensitivity of streamflow to ongoing climate and land cover changes. For instance, the Amazon basin has increasing (northern areas; 10, 12, 15-16 Fig. 4), decreasing (south-east areas; 21-24)) and low changes (south-west areas; 17-20) in streamflow due to climate changes with land cover changes intensifying or diminishing these effects (fig. 5). These patterns could be related to transitional process over time such as deforestation [*Zemp et al.*, 2017].

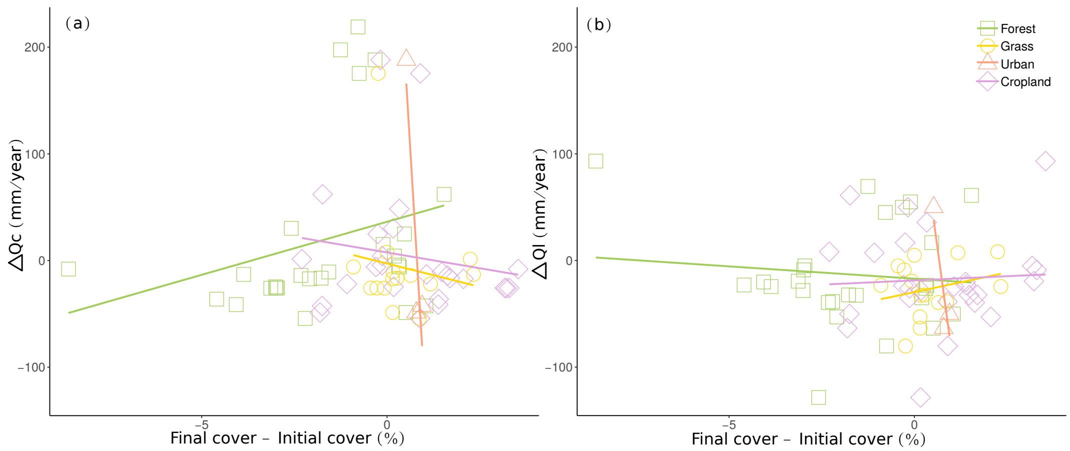

Figure 6. Land cover changes against both, changes in streamflow due to climate changes (a) and changes in streamflow due to land cover changes (b). We removed the autocorrelation (to only use independent data) associated to nested basins in the Amazon, Paraguay and Mackenzie (part of Canada basins) rivers (Supplementary S1).

Our results can also show a single pattern in one region, i.e., a clear reduction or increase in streamflow over time. The Paraguay river reflects a dampening in streamflow in all basins, which is clearly explained by reduction due to climate and land cover changes. This is probably related to a decrease in precipitation over time, that consequently affects land cover distribution (e.g., desertification). This particular region can be affected by reduction of the atmospheric moisture coming from adjacent regions (the Amazon basin is an important source of the precipitation in the Paraguay basin *Marengo* [2006])

Further, there are observed changes in streamflow only depending on changes in climate. These cases are represented by the northern regions (Canada and Siberia; there is a common increase in streamflow due to climate changes in around 100%) in our sample. This is probably related to ongoing global atmospheric changes related to climate change that affects precipitation (the south of Canada has been becoming wetter and warmer *Zhang et al.* [2000] and something similar occurs in Siberia *Yang et al.* [2002].

Although the results obtained using this method are accurate, according to the comparison between these patterns and the changes in land cover types (i.e, most of the changes found in streamflow after applying the elasticity method due to land cover changes, match with measured changes in land cover data), these results do not account for all the effects produced by land cover changes in large areas. Particularly in large basins both, climate and land cover, are closely related through surface-atmosphere interaction, hence separate both effects in streamflow is a complex task in these large areas.

There is a current scientific debate about the importance of vegetation on surface water availability [*Andréassian*, 2004; *Ellison et al.*, 2012]. Although there is no clear consensus among the studies, we can say that the relevance of a vegetation affecting streamflow depends on the spatial scale [*Zhang et al.*, 2016]. Most of the studies analyzing the effects of the land cover changes in streamflow, are developed on the catchment scale [*Brown et al.*, 2005], where a common result is that, for instance, reduction of forest cover leads to a increase of streamflow [*Bruijnzeel*, 2004]. On the contrary, there are fewer studies relating the influences of land cover changes on streamflow in regional-to-global scale [*Zhou et al.*, 2015].

It is evident that climate is one of the main important factors affecting the presence or absence of a type of vegetation (land cover). But it is also important to highlight that the vegetation in a large region could also affect the climate variables, due to different physical processes (e.g precipitation recycling, *Eltahir and Bras* [1994]; *Spera et al.* [2016]), affecting also the surface water availability via streamflow. Additionally, there are other biophysical mechanisms associated with particular vegetation, such as forest, that could influences rainfall and/or streamflow such as stomatal control from a large area of leaves [*Berry et al.*, 2010; *Costa and Foley*, 1997; *Katul et al.*, 2012] and condensation nuclei emissions [*Pöschl et al.*, 2010] affecting moisture in atmosphere, and influences on soil moisture distribution [*Nadezhdina et al.*, 2010; *Nepstad et al.*, 1994; *Lee et al.*, 2005; *Bond et al.*, 2002].

The specific internal ecosystems and external conditions of each region determine the development of all those mechanisms associated with land cover [*Wang and Fu*, 2013; *Stickler et al.*, 2013; *Coe et al.*, 2009]. In this way, the Amazon basin has a very mature forest and a strong feedback structure between surface and atmosphere that govern the water balance, which even affect the nearby regions such as the Parana basin [*Arraut et al.*, 2012; *Bonan*, 2008]. Accordingly, the results from applying streamflow elasticity to climate could be affected by this relation. For instance, in these large forested basins, a percentage of precipitation depends on evaporation from the same basin (precipitation recycling, *Van der Ent et al.* [2010]; *Eltahir and Bras* [1994]), i.e, changes in land cover could lead to changes in precipitation in the basin. Nevertheless, it is a challenge to separate the real changes in climate from the changes in climate due to changes in land cover. Finally, we consider that future related studies should focused on finding a method to separate the real changes in streamflow due to climate changes from the real changes in streamflow due to land cover changes. This method should account for all above listed biological and physical mechanisms associated with land cover and should be capable of represent the surface-atmosphere water exchanges presented in large basins.

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Chapter 5

Conclusions

Overall, the findings are consistent with the premise that forests enhance surface water availability in large basins. This is reflected by two patterns governing the water balance partitioning: less forested basins match with evaporation as the main dominant variable in the partitioning and more forested basins match with a approximately equally divided partitioning into evaporation and runoff. These findings support that, although the partitioning mainly depends on energy and water limitation conditions, the partitioning in large basins is also influenced by physical and biological mechanisms associated with the presence of vegetation. Moreover, forest is an effective descriptor of basin attributes that are relevant for characterizing long-term water balance partitioning in large basins of the world. Through this result, the main objective of this thesis is fulfilled due to a general and globally-applicable pattern was found to relate surface water balance to the presence of forest. The pattern found is in accordance with initial hypothesis: forest cover exert control over surface water balance.

Additionally, this research concluded that forest and some associated soil properties have a strong correlation with water balance partitioning in tropical and temperate basins, while in boreal basins other physical attributes related to snow-melt processes dominate the partitioning. The ongoing land cover changes in different regions such as deforestation in tropics, forest die-off in temperate regions and afforestation in boreal regions may lead to changes in surface water availability. This comparison between different regions and ecological and physical variables support the results and main objective of this research.

Finally, a critical implication is that forest loss may lead to reduce surface water availability. More mechanistic descriptions of the role of vegetation, forests in particular, on hydrological partitioning is required to fundamentally advance in understanding global change effects on water resources. By discriminating physical and ecological mechanisms that define key-ecohydrological processes in review basins, management and adaptation strategies to global change impacts can be more effectively implemented, so that impacts on ecosystem function and ecosystem services can be managed and minimized. This study provides insights to developing this fundamental challenge for science in the anthropocene. The most common approaches to separate both effects do not account for all scientifically identified mechanisms associated with forest in large areas (energy-water limited functions, parametric models, and coupled surface-atmosphere models).

Quantifying all the physical an ecological mechanisms developed through surface-atmosphere exchanges that control hydrological water balance is proposed as a next step of this research. This is a critical requirement to guarantee water sustainability in most regions of the world.

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Appendix A

Supplementary: Chapter 1-Global synthesis of forest cover effects on long-term water balance partitioning in large basins

Supplementary: Global synthesis of forest cover effects on long-term water balance partitioning in large basins

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Table S1. Basin, rivers and countries. n: total number of gauges of each basin; (): On parenthesis are the number of gauges at each river. Rivers contained in the same basin, can share at least the same outlet point of the basin, for example, Branco and Negro rivers share the outlet points of the Amazon basin (in Obidos).

Basin	Sub-basin	n	Countries
Amazon	Branco (6), Negro (6), Solimoes-Javari (8), Solimoes-Jurua (11), Purus (11), Madeira (12), Tapajos (9)	51	Bolivia, Brasil, Colombia, Ecuador, Peru, Guyana, Suriname, Venezuela
Danube	Danube (6), Sava (4)	10	Romania, Hungary, Serbia, Austria, Germany, Bulgary, Slovakia, Croatia, Ukraine, Moldova
Lena	Lena (7), Vitim (9)	12	Russia
Mackenzie	Mackenzie-Athabasca (6)	6	Canada
Magdalena	Magdalena (8), Cauca (8)	15	Colombia
Mississippi	Upper Mississippi (15), Ohio (14), Missouri (27)	55	EEUU
Murray-Darling	Murray (4), Darling (8)	13	Australia
Orange	Orange (9)	9	South Africa, Namibia, Lesotho
Parana	Parana (6), Paraguay (7)	10	Brasil, Paraguay, Argentina
Tocatins	Ariguaia (5)	5	Brasil
Cooper	Cooper (5)	5	Australia

Table S2. Data Sources

Data	Source
Digital Elevation Model (DEM)	Global 30 Arc-Second Elevation (GTOPO30),
	Shuttle Radar Topography Mission (SRTM).
Land Cover	MODIS land cover type product (MCD12Q1)
Rainfall	ECMWF-ERA-Interim reanalysis,
	Tropical Rainfall Measuring Mission (TRMM-3B32).
Streamflow	ORE-HyBAm, Murray-Darling Basin Authority (MDBA),
	Subsecretaria de Recursos Hidricos de Argentina,
	Agencia Nacional de Agua de Brasil,
	Water Survey of Canada,
	Global Runoff Data Centre
	(GRDC) 56068 Koblenz, Germany,
	Department: Water and Sanitation-Republic of South Africa,
	United States Geological Survey.
Potential evaporation	Global Land Evaporation Amsterdam Model (GLEAM v3.0a)

Table S3. Data used to calculate correlations

Basin/Attribute Mean	Rainfall	Runoff	PotentialEvap.	Forest	Shrub-Grass-Savannas	Urban-Crop
1. Branco	2121.8145	1042.1294	1095.0331	0.8556	0.1354	0.0063
2. Negro	3023.3438	1866.4421	981.3038	0.9564	0.0374	0.0036
3. Solimoesjav	2507.2653	1366.3806	1019.0834	0.8914	0.0975	0.0080
4. Solimoesjurua	2226.1693	1014.6217	1053.1362	0.9520	0.0390	0.0070
5. Purus	2127.7948	816.1604	1105.9844	0.9090	0.0724	0.0168
6. Madeira	1641.4724	514.3794	1140.0886	0.5123	0.4709	0.0103
7. Tapajos	1966.6807	807.0126	1183.4082	0.3983	0.4579	0.1437
8. Ariguaia	1581.7253	529.5244	1175.8913	0.0125	0.9532	0.0341
9. Magdalena	2132.1895	1169.4876	965.2502	0.5766	0.1497	0.2663
10. Cauca	2565.6814	1119.4803	828.3783	0.5074	0.0954	0.3928
11. Parana	1295.8652	363.4496	1125.4907	0.1245	0.7228	0.1338
12. Paraguay	1260.8355	302.0349	1221.3251	0.1767	0.7881	0.0176
13. Mississippi	657.2122	166.6107	607.8317	0.2366	0.0983	0.6421
14. Ohio	1247.1688	619.8682	615.5850	0.7343	0.0003	0.2637
15. Missouri	476.2865	59.5760	555.3695	0.1334	0.7069	0.1566
16. Mackenzie	713.7544	308.163	677.7193	0.5778	0.3060	0.0619
17. Orange	649.5201	63.5541	859.3469	0.0000	0.9310	0.0650
18. Danube	903.5055	385.9901	493.1157	0.3810	0.0381	0.5776
19. Sava	906.4642	520.8459	548.3860	0.4834	0.0150	0.5003
20. Darling	526.1426	8.1858	950.5926	0.0083	0.8910	0.1005
21. Murray	686.1669	286.3791	827.7713	0.7373	0.0402	0.2211
22. Cooper	395.4910	15.1006	951.6092	0.0000	0.9998	0.0000
23. Lena	725.4027	430.9476	705.9311	0.7023	0.2745	0.0215
24. Vitim	750.4276	409.0767	692.1500	0.4220	0.5342	0.0403

Table S4. Correlations for the first 12 basins between land cover types and mean k values

Land cover types (mean values)	Kendall's correlation (to non-normally distributed data) /p-value	Spearman's correlation (to non-normally distributed data) /p-value	Pearson's correlation (to normally distributed data) /p-value
Forest	0.6870/0.0020	0.8581/0.0004	0.8785/0.0002
Shrub-Grass-Savannas	-0.5455/0.0138	-0.7133/0.0121	-0.6841/0.0142
Urban-Crop	0.2727/0.2496	0.3706/0.2367	0.3907/0.2092

Table S5. Correlations for the 24 basins between land cover types and mean k values

Attribute (mean values)	**Kendall's correlation** (to non-normally distributed data) /p-value	**Spearman's correlation** (to non-normally distributed data) /p-value	**Pearson's correlation** (to normally distributed data) /p-value
Forest	0.5408/0.0002	0.7319/<0.0001	0.7864/<0.0001
Shrub-Grass-Savannas	-0.4928/0.0005	-0.6755/0.0005	-0.7678/<0.0001
Urban-Crop	-0.0072/0.9804	-0.0217/0.9206	0.0845/0.6945

Table S6. Basins and regions of the approximately natural-flow rivers.

Region	**Basins**	**n**	**Notes**
Amazon	Branco, Negro, Solimoes, Purus, Tapajos, Madeira	63	Madeira has dams in the high part of the basin. They are mainly used to hydroelectric energy production.
Australia	Diamantina, Cooper Fitzroy, Gascoyne	14	
Brasil	Ariguaia	5	Before Tucuruí Dam in Tocatins basin.
Lena	Lena, Vitim	16	A dam in Vilyuy River. It is used to hydroelectric energy generation.
Mackenzie	Mackenzie-Athabasca	6	A dam in the upper Peace River (tributary), complete area 1761km2.
Magdalena	Magdalena, Cauca	16	Some dams used to hydroelectric energy production
Paraná	Paraguay	4	Before it reaches the Parana river (contain the Itaipú dam)
United States (US)	Altamaha Salmon, Yellowstone	12	

Table S7. Data used to calculate correlations in the approximately natural-flow rivers

Basin	Rainfall	Runoff	PotentialEvap.	Forest	Shrub	Urban
1. Branco	2121.8145	1042.1294	1095.0331	0.8556	0.1354	0.0063
2. Negro	3023.3438	1866.4421	981.3038	0.9564	0.0374	0.0036
3. Solimoesjav	2507.2653	1366.3806	1019.0834	0.8914	0.0975	0.008
4. Solimoesjurua	2226.1693	1014.6217	1053.1362	0.9520	0.0390	0.0070
5. Purus	2127.7948	816.1604	1105.9844	0.9090	0.0724	0.0168
6. Madeira	1641.4724	514.3794	1140.0886	0.5123	0.4709	0.0103
7. Tapajos	1966.6807	807.0126	1183.4082	0.3983	0.4579	0.1437
8. Ariguaia	1581.7253	529.5244	1175.8913	0.0125	0.9532	0.0341
9. Cauca	2565.6814	1119.4803	828.3783	0.5074	0.0954	0.3928
10. Magdalena	2132.1895	1169.4876	965.2502	0.5766	0.1497	0.2663
12. Altamaha	1199.1701	163.1477	894.037	0.2996	0.6254	0.0741
12. Paraguay	1260.8355	302.0349	1221.3251	0.1767	0.7881	0.0176
13. Salmon	648.9075	156.5756	577.2669	0.4546	0.5448	0.0006
14. Yellowstone	488.2526	87.5861	519.6634	0.0922	0.8988	0.0034
15. Mackenzie	713.7544	308.1630	677.7193	0.5778	0.306	0.0619
16. Cooper	395.4910	15.1006	951.6092	0.0000	0.9998	0.0000
17. Fitzroy	599.4655	42.5323	1076.8718	0.0022	0.9969	0.0003
18. Gascoyne	135.7816	12.2305	652.2497	0.0000	1.000	0.0000
19. Lena	725.4027	430.9476	705.9311	0.7023	0.2745	0.0215
20. Vitim	750.4276	409.0767	692.1500	0.4220	0.5342	0.0403

Table S8. Correlations for the first 9 approximately natural-flow river basins between land cover types and mean k values

Land cover types (mean values)	**Kendall's correlation** (to non-normally distributed data) /p-value	**Spearman's correlation** (to non-normally distributed data) /p-value	**Pearson's correlation** (to normally distributed data) /p-value
Forest	0.6480/0.0159	0.8201/0.0068	0.7393/0.0228
Shrub-Grass-Savannas	-0.5556/0.0446	-0.7833/0.0172	-0.7299/0.0256
Urban-Crop	0.6480/0.0160	0.7699/0.0152	0.5483/0.1264

Table S9. Correlations for the 20 approximately natural-flow river basins between land cover types and mean k values

Attribute (mean values)	**Kendall's correlation** (to non-normally distributed data) /p-value	**Spearman's correlation** (to non-normally distributed data) /p-value	**Pearson's correlation** (to normally distributed data) /p-value
Forest	0.6174/<0.0001	0.7928/<0.0001	0.7995/<0.0001
Shrub-Grass-Savannas	-0.6105/<0.0001	-0.8000/<0.0001	-0.8315/<0.0001
Urban-Crop	0.3113/0.0555	0.4378/0.0536	0.2621/0.2644

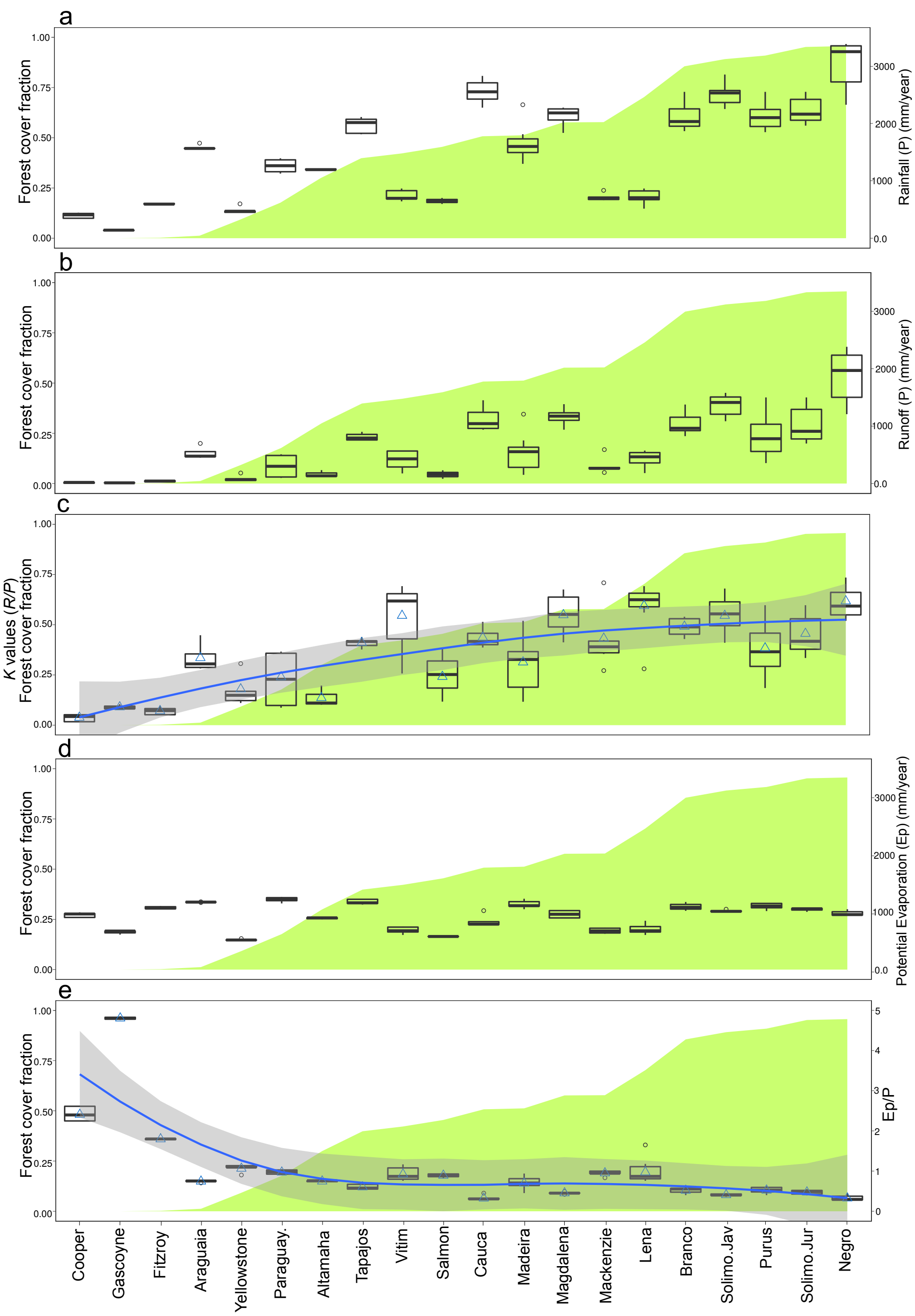

Figure S1. Distribution of spatially averaged R (a), P (b), k (c), Ep (d) and Ep/P for 20 river basins with approximately natural-flow organized by increasing forest cover fraction (green shade), for the 2001–2012 period. Boxplots describe the spatial variability of R (a), P (b), k (c), Ep (d) and Ep/P within each basin. In basins with low forest cover fraction, k-mean values (blue triangles) increase with forest cover fraction, with $k < 0.5$: E-dominated pattern. In basins with high forest cover fraction, k-mean values converge to a value around 0.5: P-halved pattern. Blue line is the LOESS fitting and grey shade is the corresponding 95% confidence interval.

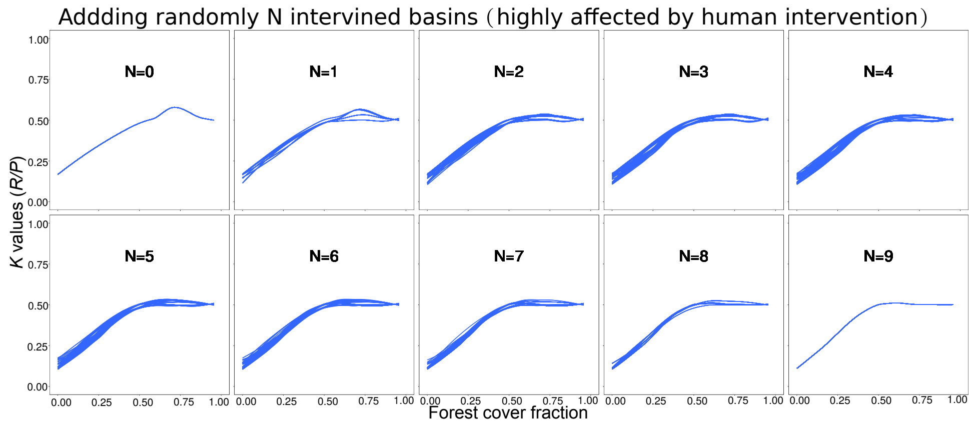

Figure S2. Sensitivity analysis for the selection of basins based on levels of human-induced disturbance. Each panel shows the LOESS fitting relating k and forest cover fraction for basins samples containing from 0 (top-left) up to 9 (bottom-right) highly intervened basins (Parana, Mississippi, Ohio, Missouri, Orange, Danube, Sava, Darling, Murray). Each panel show results for several samples that are constructed by randomly selecting the corresponding number of highly intervened basins.

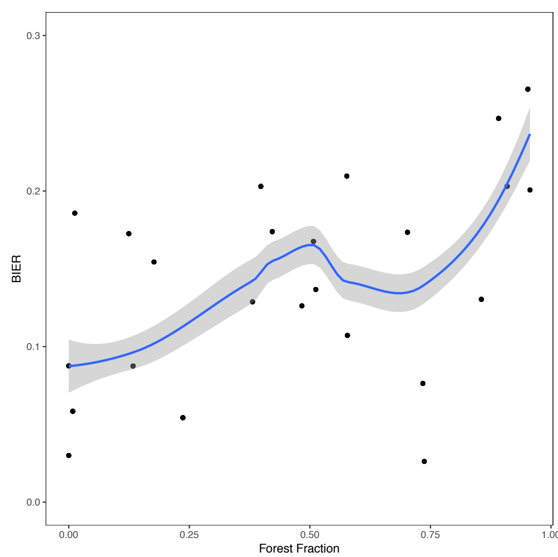

Figure S3. Forest fraction vs. basin internal evaporation recycling ratios (BIER) in the 24 large basins.

Appendix B

Supplementary: Chapter 2-Long-term water balance partitioning explained by physical and ecological characteristics in free-flowing river basins of the world

SUPPORTING INFORMATION

The following supporting information is available as part of the online article:

TABLE S 1 Data Sources

Data	Source
Digital Elevation Model (DEM)	Global 30 Arc-Second Elevation (GTOPO30), Shuttle Radar Topography Mission (SRTM).
Land Cover	MODIS land cover type product (MCD12Q1)
Rainfall	ECMWF-ERA-Interim reanalysis, Tropical Rainfall Measuring Mission (TRMM-3B32)
Evaporation	Global Land Evaporation Amsterdam Model (GLEAM version 2.0)
Streamflow	ORE-HyBAm, Murray-Darling Basin Authority (MDBA), Subsecretaria de Recursos Hidricos de Argentina, Agencia Nacional de Agua de Brasil, Water Survey of Canada, Global Runoff Data Centre (GRDC) 56068 Koblenz, Germany, Department: Water and Sanitation-Republic of South Africa, United States Geological Survey (USGS).

TABLE S 2 Basin, sub-basins and countries.

Region	Basins	n	Notes
Amazon	Branco, Negro, Solimoes, Xingú Purus, Tapajos, Ayapock, Maroni	35	Madeira was removed because it has several dams in the high part of the basin.
Argentina	Bermejo, Colorado, Neuquen, Senguerr, Chubut, Gualjaina	6	Neuquen before Cerros Colorados dam, Colorado before Casa de Piedra dam, Chubut before Ameghino dam.
Brasil	Ariguaia	4	Before Tucuruí Dam in Tocatins basin.
Australia	Diamantina, Cooper Fitzroy, Gascoyne	11	
Canada	Richilieu, Skeena, Chamouchouane, Stuart, Moisie, Fraser, Waswanipi, Natashquan, West Road, Quesnel, Melezes, North Thompson, Hayes, Chilcotin, Winisk, Ekwan, Hay, Attawapiskat, Watthaman, Missinaibi, Namakan, Beaver, Churchill, Seal, Cochrane, Ogoki, Stikine, Nass, Pembina, Lesser Slave, Clearwater Finlay, Pine, Beatton, Smoky	34	Basins classified as natural flows by Water Survey of Canada.
Congo	Congo	1	Station before the INGA dam, Brazzaville.
Lena	Lena, Vitim	10	A dam in Vilyuy River. We take stations before this tributary.
Mackenzie	Mackenzie-Athabasca	4	A dam in the upper Peace River (tributary), complete area 1761km2.
Magdalena	Cesar, Sogamoso	2	Data used before 2010, in this year the Hidrosogamoso dam get into operation.
Okavango	Okavango	1	
Orange	Orange	3	We take 3 stations before Gariep Dam.
Orinoco	Orinoco	1	Station before the tributary Caroni River, which contain the Guri dam.
Paraná	Paraguay	3	Before it reaches the Parana river (contain the Itaipú dam)
United States (US)	Altamaha, Delaware, John Day Salmon, White, Yampa, Yellowstone	10	

TABLE S 3 Correlation Tests: Tropical and temperate regions

Attribute	Spearman (rho)	Kendall (tau)	Pearson (r)
Forest	0.6397 (<0.0001)	0.4768 (<0.0001)	0.6094 (<0.0001)
Shrub-Grass-Savanna	-0.7040 (<0.0001)	-0.5175 (<0.0001)	-0.6448 (<0.0001)
Inter	0.2471 (0.0302)	0.1678 (0.0388)	0.1018 (0.3784)
Desert	-0.0495 (0.6687)	-0.0423 (0.6495)	0.2121 (0.0641)
Water	0.1427 (0.2158)	0.1095 (0.2168)	-0.0577 (0.6182)
SQ1	0.6018 (<0.0001)	0.4345 (<0.0001)	0.5849 (<0.0001)
SQ2	0.5352 (<0.0001)	0.3831 (<0.0001)	0.5270 (<0.0001)
SQ3	-0.2050 (0.0737)	-0.1253 (0.1119)	-0.0976 (0.3982)
SQ4	-0.0542 (0.6394)	-0.0400 (0.6093)	-0.1077 (0.3513)
SQ5	-0.2917 (0.0101)	-0.1933 (0.0203)	-0.2881 (0.0110)
SQ6	0.0873 (0.4503)	0.0613 (0.4722)	-0.1126 (0.3295)
SQ7	-0.2693 (0.0179)	-0.1777 (0.0224)	-0.2254 (0.0487)
Slope	-0.2108 (0.0658)	-0.1439 (0.0641)	-0.0686 (0.5531)
Soil	-0.4812 (<0.0001)	-0.3169 (<0.0001)	-0.5202 (<0.0001)
Texture	-0.2223 (0.0520)	-0.1597 (0.0426)	-0.2065 (0.0715)
Area	0.1240 (0.2826)	0.0817 (0.2931)	0.0323 (0.7805)

TABLE S 4 Correlation Tests: Boreal regions

Attribute	Spearman (rho)	Kendall (tau)	Pearson (r)
Forest	-0.1635 (0.2667)	-0.0914 (0.3599)	-0.0719 (0.6271)
Shrub-Grass-Savanna	0.5048 (0.0003)	0.3415 (0.0006)	0.3017 (0.0372)
Inter	-0.3662 (0.0105)	-0.2590 (0.0126)	-0.4047 (0.0043)
Desert	NA	NA	NA
Water	-0.1589 (0.2806)	-0.1011 (0.3144)	-0.1207 (0.4140)
SQ1	0.3283 (0.0232)	0.2323 (0.0198)	0.2016 (0.1694)
SQ2	0.3505 (0.0150)	0.2500 (0.0120)	0.2170 (0.1384)
SQ3	0.4645 (0.0010)	0.3138 (0.0015)	0.2843 (0.0501)
SQ4	0.0962 (0.5139)	0.0585 (0.5654)	0.1082 (0.4640)
SQ5	0.2526 (0.0833)	0.1623 (0.1038)	0.1890 (0.1982)
SQ6	0.2825 (0.0517)	0.1767 (0.0769)	0.1963 (0.1812)
SQ7	0.4658 (0.0010)	0.3174 (0.0013)	0.2845 (0.0500)
Slope	0.5215 (0.0002)	0.3422 (0.0005)	0.6775 (<0.0001)
Soil	-0.1667 (0.2574)	-0.0784 (0.4461)	-0.1904 (0.1948)
Texture	0.0161 (0.9137)	0.0175 (0.8649)	-0.0236 (0.8734)
Area	0.0063 (0.9663)	0.0000 (1.0000)	-0.0305 (0.8367)

Appendix C

Supplementary: Chapter 3-Streamflow changes due to climate and land cover changes in global river basins

Supporting information

Table S1: Data Sources

Data	Source
Digital Elevation Model (DEM)	Global 30 Arc-Second Elevation (GTOPO30), Shuttle Radar Topography Mission (SRTM).
Land Cover	Land Use Harmonization (LUH2)
Rainfall	Multi-Source Weighted-Ensemble Precipitation (MSWEP)
Potential Evaporation	Global Land Evaporation Amsterdam Model (GLEAM)
Streamflow	ORE-HyBAm, Murray-Darling Basin Authority (MDBA), Subsecretaria de Recursos Hidricos de Argentina, Agencia Nacional de Agua de Brasil, Water Survey of Canada, Global Runoff Data Centre (GRDC) 56068 Koblenz, Germany, Department: Water and Sanitation-Republic of South Africa, United States Geological Survey.

Table S2: Basin basic data

n	R/P	Ep/P	Forest	Grass	Urban	Crop	P	Ep	R	P_ini	P_end	Ep_ini	Ep_end	R_ini	R_end	Area
1	0.64	0.44	0.76	0.21	0	0.03	2348.4	1043.02	1499.29	2257.13	2410.85	1069.01	1025.24	1446.39	1535.49	981854.69
2	0.63	0.43	0.79	0.18	0	0.03	2446.05	1040.91	1534.36	2347.89	2509.85	1069.46	1022.36	1476.63	1571.89	1127901.29
3	0.38	0.53	0.99	0.01	0	0	2065.21	1098.89	782.68	2078.04	2044.88	1116.41	1071.16	755.6	825.55	37844.45
4	0.24	0.67	0.93	0.05	0	0.02	1736.11	1165.16	409.61	1714.88	1771.49	1171.16	1155.16	446.45	348.22	23839.6
5	0.32	0.64	0.9	0.06	0	0.03	1806.12	1162.05	575.12	1780.37	1835.31	1168.74	1154.48	538.51	616.61	34160.08
6	0.75	0.32	1	0	0	0	3041.38	986.1	2286.8	2986.46	3121.64	1001.4	963.73	2203.04	2409.22	68174.91
7	0.68	0.31	1	0	0	0	3197.87	978.21	2188.32	3140.21	3282.15	995.67	952.69	2098.42	2319.72	116208.75
8	0.44	0.55	0.97	0.02	0	0.01	2028.45	1111.09	893.21	1849.78	2098.37	1130.41	1103.53	703.45	967.46	41112.56
9	0.39	0.63	0.83	0.16	0	0.02	1859.38	1172.08	732.83	1797.48	2052.83	1174.6	1164.2	668.13	935.04	129631.59
10	0.14	0.99	0.08	0.84	0	0.08	1222.15	1208.19	176.8	1240.66	1198.36	1198.93	1220.08	198.15	149.35	22038.39
11	0.22	0.85	0.46	0.47	0	0.07	1394.16	1188.42	307.93	1402.48	1385.83	1176.39	1200.44	326.67	289.19	52725.44
12	0.17	0.86	0.31	0.65	0	0.04	1348.03	1158.17	229.84	1377.29	1331.09	1162.26	1155.8	257.27	213.97	339009.44
13	0.38	0.52	0.83	0.11	0	0.06	2166.28	1127.48	829.11	2187.45	2146.35	1118.76	1135.69	860.83	799.26	450118.73
14	0.25	0.5	0.88	0.09	0	0.03	2138.72	1077.68	544.77	2161.76	2117.03	1072.37	1082.68	571.99	519.16	456563.9
15	0.08	1.33	0.02	0.97	0	0	456.47	607.39	34.85	456.6	456.26	607.88	606.64	30.68	41.25	42460.64
16	0.13	1.04	0.05	0.88	0	0.07	1159	1207.34	151.4	1173.94	1141.07	1198.68	1217.73	175.67	122.27	568141.25
17	0.19	0.91	0.12	0.73	0	0.14	1222.57	1112.3	235.96	1252.95	1181.35	1109.04	1116.73	250.64	216.04	2393995.4
18	0.13	1.09	0.06	0.88	0	0.06	1055.36	1150.56	139.52	1074.7	1029.11	1147.27	1155.03	169.25	99.18	923486.94
19	0.19	0.91	0.12	0.73	0	0.14	1220.7	1111.09	237.52	1250.88	1179.73	1107.79	1115.56	250.6	219.76	2414707.04
20	0.18	0.9	0.13	0.72	0	0.14	1239.45	1117.71	223.1	1269.63	1198.48	1114.39	1122.22	242.31	197.03	2265722.46
21	0.36	0.49	1	0	0	0	2368.05	1160.94	841.36	2218.47	2424.14	1156.31	1162.67	689.15	898.43	62250.26
22	0.04	2.12	0	1	0	0	473.55	1002.39	20.76	445.01	484.25	1019.51	995.97	11.51	24.23	54770.39
23	0.53	0.47	0.76	0.09	0.01	0.13	1271.69	594.38	674.79	1249.64	1322.41	588.67	607.51	650.54	730.57	14987.59
24	0.54	0.47	0.76	0.1	0.01	0.13	1265.85	592.7	688.51	1242.8	1318.85	587.37	604.98	667.82	736.09	18874.31
25	0.53	0.47	0.74	0.12	0.01	0.13	1258.38	593.28	667.32	1234.57	1313.16	587.92	605.58	650.32	706.4	22203.89
26	0.51	0.48	0.7	0.14	0.01	0.15	1241.47	597.89	629.68	1215.42	1301.39	593.92	607	609.75	675.53	28713.1
27	0.51	0.49	0.67	0.16	0.02	0.14	1245.45	612.14	635.6	1220.04	1303.88	610.02	617.04	618.59	674.71	49357.53
28	0.41	0.58	0.55	0.21	0.02	0.22	1137.7	659.34	467.48	1112.08	1196.62	659.05	660	444.5	520.36	211500.73
29	0.42	0.59	0.53	0.21	0.02	0.23	1144.95	670.19	479.23	1119.34	1203.86	669.63	671.47	452.51	540.7	246109.6
30	0.22	0.76	0.74	0.09	0	0.09	731.55	553.58	160.18	748.12	698.41	548.95	562.83	172.8	134.96	15992.06
31	0.27	0.74	0.34	0.2	0.01	0.42	824.9	611.44	220.16	808.9	832.9	609.24	612.53	199.94	230.27	226509.23
32	0.11	1.08	0.01	0.64	0	0.34	548.64	592.14	61.1	562.56	527.22	588.04	598.43	65.88	53.73	1376473.59
33	0.49	0.48	0.88	0.03	0.01	0.08	1283.24	620.81	622.52	1218.32	1432.55	624.28	612.83	550.39	788.4	11796.65
34	0.27	0.76	0.68	0.08	0.06	0.18	1188.81	905.24	320.62	1219.47	1147.2	900.13	912.18	362.23	264.14	13637.74
35	0.22	0.72	0.75	0.11	0.01	0.11	1215.77	870.52	261.82	1249.75	1169.65	866.22	876.35	301.16	208.44	12932.75
36	0.25	0.76	0.66	0.18	0.03	0.14	1187.97	899.82	293.63	1220.55	1143.75	895.77	905.31	341.23	229.04	36855.53
37	0.18	1.07	0	0.91	0	0.08	485.8	518.31	87.83	510.37	448	517.77	519.14	93.67	78.86	104603.73
38	0.04	1.21	0	0.79	0	0.21	510.72	617.68	22.71	505.84	513.89	608.44	623.68	16.98	26.44	26222.99
39	0.22	0.73	0.6	0.35	0	0.03	1529.03	1121.68	336.83	1542.99	1509.71	1110.94	1136.56	322.27	357	3615547.68
40	0.06	1.57	0.04	0.94	0	0.03	683.35	1074.18	40.45	652.14	766.58	1076.71	1067.43	36.23	51.7	231849.99
41	0.51	0.46	0.51	0.44	0	0.02	963.67	438.72	488.9	933.45	992.11	441.14	436.45	474.66	502.31	173073.98
42	0.51	0.46	0.99	0	0	0	708.19	324.05	360.2	700.88	731.06	325.63	319.08	347.67	399.37	99828.32
43	0.35	0.63	0.68	0.21	0	0.1	646.48	407.18	226.98	642.86	650.82	407.51	406.79	236.28	215.82	285556.77
44	0.25	0.79	0.82	0.05	0	0.1	539.76	423.75	136.62	532.04	549.02	421.91	425.96	148.83	121.96	132602.61
45	0.09	1.01	0.1	0.41	0	0.49	449.62	455.92	42.26	437.66	487	457.36	451.39	37.69	56.55	147643.88
46	0.09	0.92	0.16	0.26	0	0.57	477.5	441.62	42.64	464.72	517.42	442.89	437.63	41.23	47.03	171029.21
47	0.09	0.97	0.25	0.26	0	0.46	465.18	450.56	43.44	451.22	508.82	451.95	446.23	38.93	57.55	413011.36
48	0.1	0.93	0.08	0.23	0	0.67	586.81	544.26	58.12	548.81	611.52	544.02	544.42	29.23	76.9	114841.04
49	0.34	0.75	0.84	0.02	0	0.02	711.23	535.24	240.49	676.74	731.93	541.05	531.74	200.27	264.63	122741.22
50	0.15	0.93	0.7	0.12	0	0.07	470.24	437.88	71.28	448.79	537.28	437.32	439.63	61.21	102.73	112763.69
51	0.08	0.82	0.79	0.05	0	0.03	506.7	414.5	38.25	488.67	563.05	414.64	414.08	30.62	62.08	278727.96
52	0.55	0.45	0.2	0.53	0.03	0.23	1012.24	457.82	552.17	1065.95	992.09	439.32	464.75	618.45	527.31	135889.91
53	0.25	0.75	0.24	0.36	0.01	0.39	662.56	499.41	164.36	623.21	710.33	491.19	509.38	143.79	189.34	157742.17
54	0.26	0.64	0.24	0.39	0.01	0.36	819.13	522.57	212.56	801.75	850.72	516	534.5	274.82	99.37	693447.02

Table S3: Changes in land cover, and changes in streamflow due to climate changes

Forest	Grass	Urban	Crop	Zheng	Sankar.	Schreiber	Oldekop	Budyko	TurcPike
0	0.02	0	0.14	170.66	186.95	169.67	209.51	187.13	163.52
-0.01	0	0	0.35	171.46	132.44	174.37	213.87	191.79	168.56
0	1.18	0	0	32.31	58.65	-2.1	4.17	0.57	-3.33
-0.03	0.45	0	0.08	23.95	44.15	26.1	33.72	29.22	23.94
-0.04	0.45	0	0.14	48.23	49.41	33.29	42.82	37.22	30.78
0	0	0	0	290.43	297.98	162.92	189.43	175.03	159.93
0	0	0	0	230.93	223.26	156.25	180.35	167.33	153.66
-0.01	0	0	0	247.6	288.41	181.25	224.54	199.59	172.43
-0.02	0.04	0	0	215.54	249.3	168.18	209.06	185.09	157.78
-0.22	0.11	0	0.22	-16.99	-18.11	-15.23	-19.24	-16.79	-12.6
-0.08	0.11	0	0.16	-12.02	-13.37	-12.12	-16.53	-13.86	-10.11
-0.05	0.09	0	0.34	-2.45	-5.07	-13.54	-16.48	-14.7	-12.18
-0.05	0.25	0	0.22	-54.14	-61.63	-30.4	-39.14	-34.13	-28.74
-0.03	0.25	0	0.06	-35.13	-27.54	-19.76	-24.7	-21.88	-18.87
0.39	0.06	0	0	0.2	0.3	0.03	0.05	0.04	0.01
-0.44	0.1	0	0.23	-17.32	-19.67	-11.25	-14.08	-12.35	-9.11
-0.24	-0.02	0	0.23	-17.96	-19.29	-27.88	-34.74	-30.56	-24.22
-0.36	0.05	0	0.32	-16.24	-30.65	-13.62	-16.48	-14.72	-11.16
-0.24	-0.02	0	0.22	-17.34	-19.54	-27.96	-34.85	-30.65	-24.28
-0.24	-0.02	0	0.23	-21.46	-25.36	-25.77	-32.16	-28.27	-22.43
0	0	0	0	92.45	85.49	106.64	126.24	115.09	103.21
0	0.86	0	0	13.55	11.28	6.39	5.77	6.2	3.72
-0.01	0.11	0.72	0	16.47	43.32	46.67	51.27	48.67	45.91
-0.01	0.01	1.06	-0.01	18.08	39.24	51.15	56.76	53.59	50.23
-0.01	0	1.35	0	16.15	33.04	51.96	57.87	54.53	50.98
-0.01	0.04	0	-0.02	35.11	48.85	57.97	66.3	61.57	56.55
0	0.05	0.23	-0.06	49.78	63.31	60.24	70.44	64.64	58.45
0.03	0.03	0.43	-0.13	63.92	52.01	54.48	66.46	59.51	51.82
0.04	0.04	0.41	-0.14	61.68	76.59	55.31	67.42	60.38	52.58
0.02	0	0	-0.21	-31.22	-35.44	-22.16	-28.57	-24.73	-19.87
0.07	1.51	0	-0.09	5.93	4.29	10.27	12.5	11.17	9.51
0.5	0.21	0	-0.14	-18.08	-19.51	-9.34	-11.41	-10.14	-7.61
0	0	0.82	-0.02	250.43	198.22	159.76	192.19	173.78	154.18
0	0	0.36	-0.14	-66.58	-72.51	-37.58	-47.84	-41.7	-33.89
0.01	0	0.65	-0.16	-57.41	-61.46	-31.78	-40.28	-35.22	-29.07
0.01	0	0.31	-0.13	-62.22	-77.49	-35.72	-45.23	-39.54	-32.32
0	0.03	0	-0.13	-17.6	-17.33	-23.56	-28.35	-25.41	-19.67
0	0.14	0	-0.11	0.06	7.28	0.11	0.04	0.08	0.2
0	0.05	0	-0.08	15.18	14.22	-18.35	-24.73	-20.93	-16.22
0	-0.02	0	0.07	2.18	0.5	17.97	19.05	18.44	12.79
0	-0.01	0	0	28.08	25.14	45.69	54.68	49.61	44.26
0	-1.32	0	0	30.22	25.71	25.71	31.57	28.26	24.77
0	-0.02	0	0.06	3.23	3.1	4.81	6.02	5.31	4.5
0	0	0	-0.02	1.18	-1.75	6.64	7.95	7.16	6.14
0	0.16	0	-0.02	9.92	5.72	9.9	12.13	10.77	8.33
0.02	0.04	0	-0.01	5.24	5.73	9.53	11.84	10.43	8.25
0	0.12	0	-0.02	10.76	7.28	11.12	13.72	12.13	9.51
0.02	0.89	0	-0.1	12.48	17.04	11.93	14.66	13	10.4
0	0	0	0	39	28.05	35.85	45.66	39.79	32.4
0.01	0	0	-0.04	16.58	25.71	25.55	31.33	27.8	22.3
0	0.06	0	0	14.18	7.93	10.25	12.75	11.24	9.2
0.11	-0.18	0.11	-0.04	-115.68	-156.17	-72.39	-90.44	-80.27	-69.53
0.04	0.14	0	-0.08	20.08	22.92	33.39	40.1	36.08	31.01
0.07	0.03	0	-0.09	-54.66	-83.49	16.01	18.01	16.84	15.49