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Key Points:

- Water yield and hydrological regulation are two complementary water-related ecosystem services that not always follow the same trend

- Hydrological regulation is the capacity of catchments to attenuate the intensity and timing of water inputs and transfer them to a stream

- The "Baseflow yield coefficient" might a useful simple index to summarize both water yield and one aspect of hydrological regulation

Abstract

The rise of the ecosystem services concept has brought some characteristics of the water cycle to the attention of a broader audience who are not necessarily intrinsically familiar with hydrological processes. When referring to water supply, the term "hydrological regulation" (or streamflow buffering) is frequently used by non-hydrologists, yet they are often lost in the intricacies of the processes that drive it leading to confusion and misunderstandings. It is not uncommon that several water security challenges that require the conservation or enhancement of hydrological regulation end up prioritizing actions that aim at increasing water yield instead. Here, I present a simple index named "baseflow yield coefficient" (BYC), which is calculated as the ratio between baseflow (or dry season flow) and precipitation for a given priod of time. Although quite simple, this might be a powerful tool to quantify both water yield and hydrological regulation and to provide an accessible and transparent variable that addresses the aforementioned issue. By using this index, I aim to guide the conversation to achieving more effective water security investments while, at the same time, seek to prevent having to revive the misunderstanding between water yield and hydrological regulation, so that we can move directly on to more relevant matters.

Plain Language Summary

When dealing with water-related problems, many of them are not only about how much water is available in a river (water yield) but about how and when such river flows occur. This is what we, hydrologists, often call "hydrological regulation" or streamflow buffering. Usually, several projects need to improve streamflow buffering but they end up implementing actions that are aimed at increasing water yield instead. To help solve this misunderstanding, I present here a simple index, which I called "baseflow yield coefficient" (BYC) and that

measures how much of the rainfall over a watershed is stored and converted into baseflow (or dry season flow) in a given period of time, for example, a year. I expect that the use of this index will help prioritizing actions that are effective to solve the water-related problems that deal with streamflow buffering more clearly.

1 Water yield and hydrological regulation

Hydrological processes play a fundamental role in many ecosystem services. Most directly, water supply is one of the major ecosystem services, including chacracteristics such as quantity, quality, location, and timing, and is related directly to minimizing drought risks. Yet ecosystems provide and support several other water-related services such as flood risk mitigation, controlling contaminant transport, supporting nutrient flows, biomass production and many more (Brauman, 2015). All of these are related to hydrological processes in complex and intricate ways, making it difficult for ecosystem managers to understand how catchment interventions –which affect hydrological processes– propagate into changes in the resulting ecosystem services.

Hydrologists will typically define *hydrological regulation* as the capacity of catchments to assimilate climate inputs and, by interactions with their biophysical characteristics, store and transfer water to a stream while attenuating the intensity and timing in the resulting flows (**Figure 1**). Often, hydrological regulation is associated to the ability of terrestrial ecosystems to provide a seasonal buffer of streamflow, i.e., to store water during the rainy seasons and to sustain dry season flows (Minaya et al., 2018).
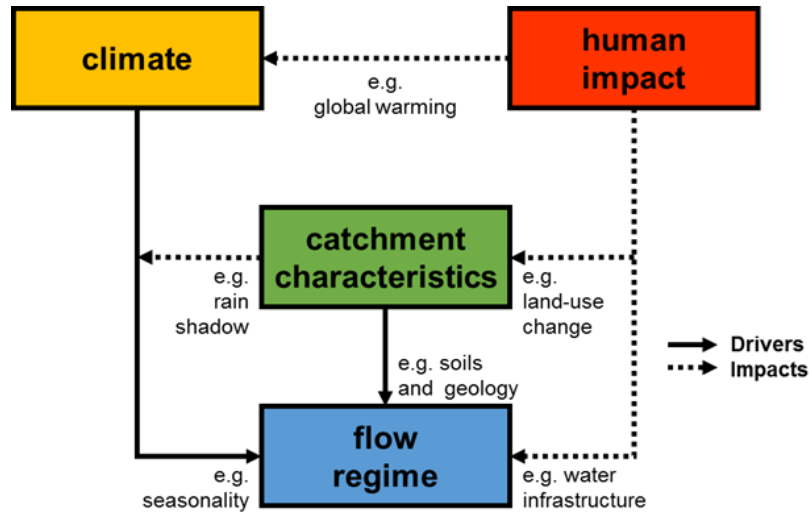

Figure 1. Conceptualization of hydrological regulation and its drivers. Hydrological regulation can be defined by the relation between climate input and flow regime, which is controlled by catchment characteristics and influenced by

human impacts on climate, biophysical properties, and on flow directly.

Several processes in a catchment contribute to such regulation capacity and they are often associated to water stores: vegetation, the unsaturated soil layer, the saturated soil and underlying bedrock (aquifers), water bodies (including wetlands and lakes), glaciers, among others. Each elements' capacitiy depends on specific properties, such as storage space and water transit time, and governing biophysical processes. Although water retention is intrinsic to hydrological regulation, those two concepts are specific and should be used accurately. Lü et al. (2015) define water retention as "the capacity of ecosystems to hold part of water input from precipitation at certain spatiotemporal scales", whereas hydrological regulation is defined as "the capacity of ecosystems influencing the hydrological cycles across space and time". Hydrological regulation is then understood as a more holistic and inclusive ecosystem service than the mere storage of water and thus cannot be replaced simply by building artificial reservoirs or dams.

In the provision of water, the concept of hydrological regulation is often confused with that of *water yield*, i.e. the amount of precipitation that is effectively transferred to river flow. Terrestrial ecosystems do not "create" water, but move and modify flows by means of regulating services enabled by biophysical processes (Brauman, 2015). The water yield of a catchment is sometimes seen as its water "factory" capacity, for example, feeding from inputs such as precipitation volumes and fog captured by vegetation, and suffering losses in the form of evapotranspiration rates or deep percolation. On the other hand, hydrological regulation is sometimes associated with the "sponge-effect". This metaphor works well in many aspects: catchments have a limited water storage capacity that can be surpassed, water might not be absorbed but repelled when the soils are too dry, it builds a drainage lag time, etc.

Both water yield and hydrological regulation are affected by catchment management (e.g., land-use change) but not always in the same direction and magnitude, and sometimes constituting a trade-off. For instance, planting (exotic) trees in natural grasslands may increase hydrological regulation –because of an improved soil infiltration capacity caused by plant roots– but will often reduce water yield –because exotic tree species transpire more water and might capture less fog than native short vegetation– (e.g., Buytaert et al., 2007; Ferraz et al., 2013; Bonnesoeur et al., 2019). Although water yield and hydrological regulation are both fundamental for the reliable supply of water for people, there is a widespread confusion between their roles. Unfortunately, it is not uncommon to observe large investments in forestation projects that are justified as water conservation but result in a diminished water yield that affects local communities (Bonnesoeur et al., 2019). Similarly, several water security challenges that require the conservation or enhancement of hydrological regulation, for example, for drought control or dry season flow reliability, conclude in the implementation of actions that aim at increasing total water yield by maximizing indices such as the runoff coefficient. To address this challenge, I suggest the use of a hydrological index that can capture both hydrological regulation and water

yield in a simple manner that can be used by practitioners and non-hydrologists involved in water-related projects.

2 The Baseflow Yield Coefficient

Several indices have been developed to summarize and quantify different aspects of the flow regime and to monitor its natural state or its degree of alteration or restoration progress (e.g., Poff, 1996; Richter et al., 1996; Clausen and Biggs, 2000; Baker et al., 2004; Mathews and Richter, 2007). However, many of them might be redundant because hydrological indices are calculated from the same streamflow data (Olden and Poff, 2003). Two popular simple indices are commonly used in hydrological studies and watershed management to quantify water yield and hydrological regulation, respectively. The *runoff ratio* (RR) is the relation between average annual discharge (Q) and average annual rainfall (P) (**equation 1**). The *baseflow index* (BFI) is the ratio between baseflow volume (BF) to total flow volume (Q) (**equation 2**), and is usually interpreted as the proportion of river discharge that originates from internal catchment stores such as groundwater. The baseflow can be estimated using hydrograph separation either by measurement or calculation using one of several methods available (e.g., Gustard et al., 1992; Chapman, 1999; Eckhardt, 2008; Gonzales et al., 2009).

$$RR = \frac{Q}{P} \ (1)$$

$$BFI = \frac{\mathrm{BQ}}{Q} \ (2)$$

I propose to combine the BFI and the RR in a single index (**equation 3**) to quantify the amount of baseflow compared to total precipitation (**equation 4**). I name this index *baseflow yield coefficient* (BYC). The larger the BYC, the better the hydrological regulation capacity of a catchment because the index will be directly related to the generation of baseflow and thus to the mitigation of quick flow or surface runoff. Similarly, the larger the BYC, the better the water yield because the amount of rainfall water that is effectively converted into river flow, particularly baseflow, is also important for water privision purposes. Therefore, the BYC is an indicator of both hydrological regulation and water yield.

$$BYC = BFI * RR \ (3)$$

$$BYC = \frac{\mathrm{BF}}{P} \ (4)$$

The BYC is a simple index yet potentially very useful for optimization exercises. In summary, it is not only important how good the streamflow buffering capacity of a catchment is, but also how much water is readily available for use. Complementarily, not only the amount of total water produced in a catchment is valuable, but also how much of that water does not run immediately after a storm event and is effectively stored internally and released afterwards. Lastly, because the BYC can be calculated using equation 3, many studies that already report the BFI and the RR can easily compute this index.

3 Relationships between BYC and other indices

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To provide some calculations on the value of the proposed BYC, I use data from the Regional Initiative for Hydrological Monitoring of Andean Ecosystems (iMHEA). The iMHEA dataset is from a network of paired headwater catchments ($<20\,\mathrm{km}^2$) covering three major biomes in 9 locations of the tropical Andes. The network is designed to monitor the impacts of land-use change and watershed interventions on the hydrological response, with each catchment representing a typical land use and land cover practice within its location (Ochoa-Tocachi et al., 2018). **Figure 2** shows a comparison between BYC with several climatic and hydrological indices and catchment physiographic descriptors derived from iMHEA's data.
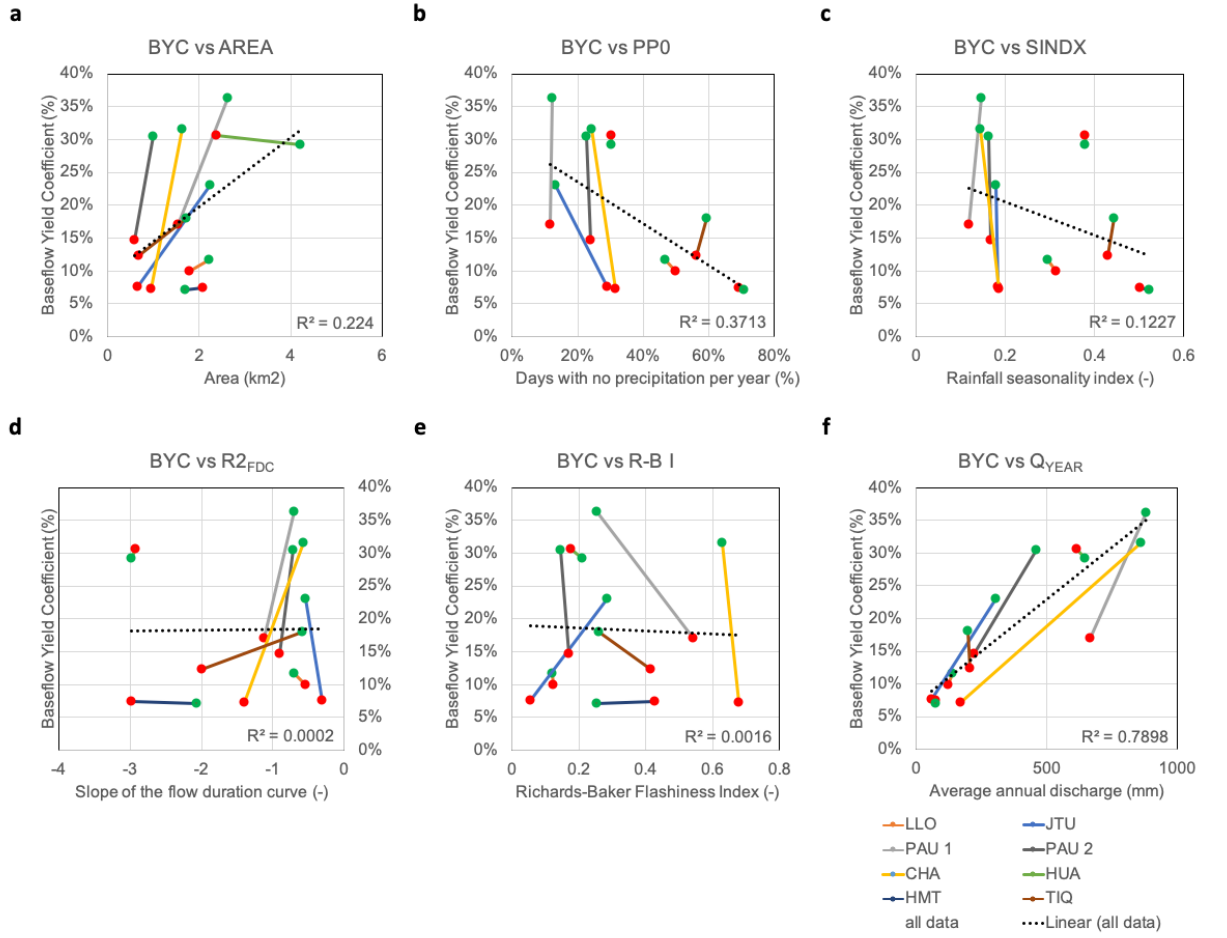

Figure 2. Comparison between the Baseflow Yield Coefficient (BYC) and other catchment indices: (a) catchment area, (b) percentage of days with zero precipitation per year (PP0), (c) rainfall seasonality index (SINDX), (d) slope of the mid third of the flow duration curve ($R2_{FDC}$), (e) hydrological regulation

index (IRH), (f) average annual discharge (Q_{YEAR}). Paired catchments are joined by straight lines. The colour of the lines represent different locations in the monitoring network. Green circles represent reference state catchments and red circles represent altered catchments by different types of land use. The black dashed lines show linear correlations between BYC and the other variables. The R^2 values are reported for each linear regression at the bottom right corner of each plot. More details on the data are available in Ochoa-Tocachi et al., 2018.

The area of the analyzed catchments is similar between pairs (**Figure 2a**), except for pair HUA where the reference catchment is considerably bigger. In this pair, particularly, the value of the BYC decreases slightly from the reference state towards the altered state; however, both values of BYC are high compared to others in the network. In general, the values of BYC decrease from the reference catchment states (green circles) towards the altered pairs (red circles) indicating a negative relationship between catchment alteration and baseflow. Both climatic indices (PP0 and SINDX) show that paired catchments are subject to similar climatic regimes and, although BYC reduces with an increase in seasonality and in days with zero precipitation, it is not signiticantly correlated to these variables (**Figure 2b,c**). This indicates that most of the effect on baseflow will be produced by changes in land use and management between the paired catchments. This was also observed in a detailed analysis on the regionalization of impacts of land use on the hydrological response of tropical Andean catchments (Ochoa-Tocachi et al., 2016).

Figure 2(d,e) shows the relationship between BYC and two indices of hydrological regulation: the slope of the flow duration durve ($R2_{FDC}$) and the Richards-Baker flashiness index (R-B I). These indices are not correlated to BYC and capture different aspects of the hydrological regultation capacity is. The flow duration curve, visually and quantitatively, eliminates the time variable from the streamflow timeseries and reorganizes it using a plotting position. The $R2_{FDC}$ index is useful to analze the overall hydrological regulation in a probability context, particularly comparing medium-high flows (percentile 66th) vs medium-low flows (percentile 33rd). For instance, a steep slope of the flow duration curve indicates large magnitude differences between the hydrological response to input precipitation, whereas a more horizontal curve represents a buffered behavior and larger storage capacity (Ochoa-Tocachi et al., 2016). The R-B I quantifies oscillations in daily flows relative to total flow and how often and in what magnitude those oscillations happen (Baker et al., 2004). Naturally, the quicker the daily flow changes, the worse the hydrological regulation capacity of a catchment. Because baseflow is an important component of the flow hydrograph that represents the role of internal catchment stores such as groundwater (Bloomfield et al., 2021), and the fact that BYC is independent from $R2_{FDC}$ and R-B I, this would mean that BYC is capturing a different aspect of the catchment hydrological regulation: the relative magnitude of the generated baseflow volume as a function of precipitation. **Figure 2(f)** shows that BYC is correlated to the average annual discharge (Q_{YEAR}), although the total flow variable was eliminated from the calculation of BYC in equations 3

and 4. This thus indicates that BYC might also be a useful indicator of water yield.

4 Conclusions

From the above, it can be concluded that the proposed Baseflow Yield Coefficient (BYC) might be a useful indicator of both hydrological regulation and water yield. Despite its simplicity, this index can be a powerful tool to summarize complex aspects of cachment hydrological response. It is indeed its simplicity that renders the BYC practical and readily usable. Because it can be calculated by multiplying two other popular indices (the baseflow index and the runoff coefficient) the BYC can be computed easily using commonly reported data. A clear limitation is, of coursem, the hydrograph separation needed to extract the baseflow timeseries from the total flow. However, this has been widely studied in the hydrological sciences. Additionally, the example shows that the BYC is not correlated to other two indices of hydrological regulation (the slope of the flow duration curve and the Richards-Baker flashiness index) and thus might be capturing a different aspect of the hydrological regulation service.

The BYC might prove extremely useful for broader non-hydrological audiences. Although quite simple, it can quantify both water yield and hydrological regulation and become an accessible and transparent optimization variable in water-related projects. Because several water security challenges require to consider simultaneously the conservation or enhacement of hydrological regulation as well as water yield, the BYC can be seen as a common ground. By using this index, I aim to guide the conversation to achieving more effective water security investments while, at the same time, seek to prevent having to revive the misunderstanding between water yield and hydrological regulation, so that we can move directly on to more relevant matters both scientifically and professionally.

Finally, the BYC index proposal may be defined as a "Columbus' Egg" (Benzoni, 1565), which refers to an idea or discovery that seems simple or easy after the fact. The BYC can thus be considered "novel" and valuable because it is unpretentious and can be very practically implemented.

Data Availability Statement

The data used in the study are openly available at Figshare via https://doi.org/10.6084/m9.figshare.c.3943774 (Ochoa-Tocachi et al., 2018).

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