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Assessing hydrologic alteration: Evaluation of different alternatives according to data availability

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ABSTRACT

The natural flow regime of rivers across the world has been largely modified. Understanding the extent to which the flow regime deviates from natural conditions is necessary for designing sound management and restoration measures. In this regard, 'Indicators of Hydrologic Alteration' is currently considered one of the most effective approaches for assessing hydrologic alteration (HA). However, several generalized drawbacks such as the climatic variability between the pre- and post-impacted series and the scarcity of hydrological data in many impaired rivers should be addressed. In this study, a protocol with the following five alternative designs based on data availability is presented: (1) Paired-Before–After Control–Impact (BACIP), (2) Before–After (BA), (3) Control–Impact (CI), (4) Hydrological Classification (HC) and (5) Predicted Hydrological indices (HP). BACIP compares the status of the impacted gauge before and after the perturbation is started, in addition to controlling for natural climatic changes. Hence, it has been considered as the reference benchmark for all other designs. When this protocol was applied to 11 reservoirs situated in the northern third of the Iberian Peninsula, the BA design was able to correctly identify most of the non-significant HA but failed in almost one quarter of the significant alterations. Similarly, BACIP and CI showed an agreement of >80%. This suggests that the method is suitable when proper data are unavailable for BACIP or BA. In addition, our results indicated that the critical thresholds for HA varied depending on the hydrological index being considered. Significant HAs ranged from <5% for the number of days with increasing and decreasing flows to >64% for the duration of low-flow pulses. To delineate adequate thresholds, further research combining hydrological analyses with the biological response to the HA is warranted. Finally, the application of HC and HP designs revealed a significant degree of uncertainty related to the intra-class variability and the predictive error of the models. Therefore, 25% of the analysis could not be evaluated. However, in the evaluable cases, the HC and HP designs correctly assessed >75% of the HA, which highlighted the potential of this method in cases of scarce streamflow data.

1. Introduction

The functioning of freshwater ecosystems is closely related to its natural flow regime at multiple spatial and temporal scales (Biggs et al., 2005). However, the natural flow regime of most rivers has been largely altered during the last century (Poff et al., 2007; Zarfl et al., 2015), which has led to significant degradation of these ecosystems. The dominant effects of hydrological alteration (HA) are mainly related to the modification of the seasonality (Döll et al., 2009) and natural disturbing-flow episodes (i.e., floods and droughts; Lake, 2007). The homogenization of seasonal flows modifies in-stream habitat patterns, promotes the establishment of non-native species and decreases biotic heterogeneity (Moyle and Mount, 2007). The modification of flood and drought patterns interferes with the life cycle of many organisms (Lytle and Poff, 2004), degrades the riparian area (Jolly, 1996), modifies channel

Abbreviations: HA, hydrological alteration; IHA, indicators of hydrologic alteration; HI, hydrological index; BACIP, Paired-Before–After Control–Impact design; BA, Before–After design; CI, Control–Impact design; HC, hydrological classification design; HP, predicted indices design; IHA_{BA}, percentage deviation of each hydrological index of the post-impact series relative to the pre-impact series within the Before–After approach; IHA_{CI}, percentage deviation of each hydrological index of the post-impact series in the impacted gauge relative to the control gauge is calculated within the Control–Impact approach; IHA_{HC}, percentage deviation of each hydrological index calculated from the post-impact series in the impacted gauge relative to the mean hydrological index value of the hydrological class; IHA_{HP}, percentage deviation of each hydrological index calculated from the post-impact series relative to the predicted hydrological index for the river segment where the impacted gauge is located.

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and floodplain structure (Milner et al., 2013), or increases siltation of spawning areas (Magilligan and Nislow, 2005), among several other effects (Lake, 2007). Therefore, it is now widely accepted that some degree of similarity to the pre-impacted flow regime characteristics is required to maintain ecosystem processes (Arthington et al., 2006; Galat and Lipkin, 2000; Schneider et al., 2013). In this regard, the first step towards adopting appropriate conservation measures is identifying the extent to which the flow regime deviates from natural conditions (Black et al., 2005). One of the most robust approaches of determining HA is the site-specific comparison of pre- and post-impacted flow series (McManamay et al., 2012); thus, the 'Indicators of Hydrologic Alteration' (IHA; Richter et al., 1996) has seen worldwide use (e.g., Fernandez et al., 2012; Magilligan and Nislow, 2005; e.g., Maingi and Marsh, 2002; Yang et al., 2008). IHA has evolved into the 'Range of Variability Approach' (Richter et al., 1997) and the 'Environmental Flow Components' (Mathews and Richter, 2007) to provide environmental flow recommendations, although, one of the first steps of all these methods is the assessment of the HA. IHA summarizes pre- and post-impact series in a number of hydrologic indices (HIs). Then, the IHA is defined for each HI as the magnitude of change between the two periods. Despite the widespread application of the IHA, it presents several drawbacks that should be addressed to completely understand and determine the degree of HA of a river.

First, the results of the IHA are originally presented in terms of the magnitude of the impacts rather than as a statistical value for the null hypothesis of similar pre- and post-impact conditions (Richter et al., 1996). Indeed, most of the applications of the method do not define critical IHA thresholds that produce significant HA (Hu et al., 2008; Magilligan and Nislow, 2001), or they do so arbitrarily (Caruso, 2013; Fernandez et al., 2012; Yang et al., 2008). On the contrary, the definition of critical IHAs based on objective statistical methods is paramount to reducing the uncertainty in assessing HA.

Second, the natural climatic differences between the pre- and post-impact periods may exert a significant influence on the IHA outcomes (Zhao et al., 2012), which may interact with other hydrologic perturbations (Naik and Jay, 2011; Schneider et al., 2013). In this regard, the application of the IHA method would uniquely indicate the occurrence of a change in state. However, it would not allow us to distinguish a change caused by the reservoir operation from a change that would have occurred even if the activity was not started (Downes et al., 2002). Using the yearly values of the HIs at a control site as a measure of the unmodified state of the system through time, it is possible to statistically compare what would have occurred in the impact site in the absence of the perturbation. This represents the basis for the Paired-Before–After Control–Impact (BACIP) design (Stewart-Oaten et al., 1992; Downes et al., 2002). The BACIP design allows testing for significant differences in a variety of possible situations, and it helps to differentiate changes not caused by the perturbation (Fig. 1A–C) from those caused by the perturbation (Fig. 1D–F). Moreover, the BACIP design allows identifying changes in cases of natural differences between the control and impact sites (Fig. 1B and F). In cases of the perturbation generating an impact on the flow regime, several situations can be found. For instance, when the dam operation is the only factor affecting the hydrology, the HA can be easily detected (Fig. 1E). On the contrary, when other factors come into play (e.g., climate variability), the post-impact hydrological patterns may resemble the previous pre-impact conditions (Fig. 1D and F) and mask the actual HA caused by the dam.

Another significant factor that can hamper the application of the IHA method is the availability of proper flow records (Carlisle et al., 2010) provided by gauging networks. These networks often lack appropriate pre-impact series (Eng et al., 2013). Thus, strategies that provide alternative means of assessing HA are needed. In the past years, hydrological classifications have been shown to be suitable as a sound context for stratifying rivers in management units when evaluating the HA (Arthington et al., 2006; Poff et al., 2010). In addition, several authors have used statistical approaches to predict the unimpaired value of specific HIs (before the dam is constructed) to complete river networks based on climate, catchment configuration, geology and land uses (Knight et al., 2011; Sanborn and Bledsoe, 2006). However, to the authors' knowledge, no study has accomplished a quantitative comparison between these two alternative strategies and the IHA.

In this paper, a protocol for assessing HA with the following five alternative designs, which depend on the availability of hydrological data, is presented: (1) BACIP, (2) Before–After (BA), (3) Control–Impact (CI), (4) Hydrological Classification (HC) and (5) Predicted Hydrological indices (HP). BACIP compares the status of the impacted gauge before and after the perturbation is started, in addition to controlling for natural climatic changes and other confounding factors. Hence, it has been considered as the reference benchmark for all other designs.

The protocol was applied at 11 dams situated in the northern third of the Iberian Peninsula, with the aim of illustrating and evaluating its application. Specifically, the following steps were carried out in the study: (1) assessing the agreement between BACIP and less data-intensive designs (BA and CI), (2) determining the critical IHA thresholds that generate a significant HA and (3) evaluating the suitability of alternative strategies to assess the HA in the absence of proper recorded flow data (HC and HP). We hypothesized that BA design would provide similar results to BACIP except for sites subjected to changes produced by factors other than the reservoir operations (e.g., change in climate conditions). Because entirely twin basins with proper data are difficult to find, the CI design would fail when other confounding factors differed between the impact and control sites. Finally, the reliability of the HC and HP designs would depend on the uncertainty associated with the intra-class natural variability and the prediction accuracy of the models, respectively.

2. Methods

2.1. A protocol to assess hydrological alterations

In this study, a systematic protocol was developed to evaluate HA (Fig. 2), enabling different analyses and comparisons. The protocol provides the following elements, which explain the main drawbacks and principles discussed earlier:

1. Statistical analyses to determine the significance of the changes between the pre- and post-impact series.
2. Control sites to isolate the HA caused by human perturbations from climatic factors.
3. Alternative designs to evaluate HA in the absence of proper pre-impact series.

2.1.1. Selection of impacted and control gauges

The first step in the protocol involves selecting the most adequate gauge to monitor the target perturbation (impact series; Fig. 2). The flow series of the impacted gauge has to cover either the pre- and post-impact periods or uniquely the post-impact period. This will determine the further analysis to be applied. The flow series quality must be assessed, and years without desirable data quality should be eliminated (Peñas et al., 2014). In addition, the length of the series could be a limiting factor based on the further design used to assess the HA. Hence, the longest possible series is recommended.

In the absence of an impacted gauge to monitor the perturbation, several other methods can be used for to assess HA (Fitzhugh and