Assessing the hydrologic alteration of rivers in Europe

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Abstract

This paper presents a European-scale analysis of hydrologic data at the resolution of the Functional Elementary Catchment (FEC). Simulated daily time-series of river flows from the PCR-GLOBWB model were used based on a hypothetic near-natural scenario where water abstractions from water bodies do not exist and the actual anthropogenic scenario with water abstractions occurring. Many hydrologic indicators describing the rivers' hydrologic regime were calculated with the Indicators of Hydrologic Alteration (IHA) methodology and software package and their deviations between the two scenarios were used as proxy metrics of rivers' hydrologic alteration or hydrologic stress. The results were indicated by mapping the hydrologic alteration on Europe's geographical FEC-level background. Indicators, mostly connected with low flow conditions, showed that Southern Europe is more hydrologically stressed due to abstractions than the rest of Europe. This work gives a general view of hydrologic stress in Europe allowing the identification of possible significant hydrologic stress on a local basis. However, to be able to determine minimum ecological flows that can ensure good ecological status, good pan-European datasets on ecological response are required.

Keywords: Functional Elementary Catchment, Hydrologic Stress, Indicators of Hydrologic Alteration, PCR-GLOBWB model.

1. Introduction

A common definition of a river's ecological flow (e-flow) is related to the amount of water required to maintain the river's ecological components, functions and services (Arthington *et al*., 2006; Brown and King, 2003). Recently, the ecological flows were considered to be integrated into the Water Framework Directive (WFD). The WFD CIS Guidance Document No 31 (CIS, 2015): *Ecological Flows in the Implementation of the Water Directive*, aims to provide an understanding of the e-flow concept and how to use it in the River Basin Management Plans (RBMPs) considering e-flows as 'an hydrological regime consistent with the achievement of the good ecological status'.

E-flow assessment methodologies are differentiated into hydrological, hydraulic rating, habitat simulation and holistic methodologies (Tharme, 2003), with the first predominating due to their simplicity. Hydrologic methodologies rely on the use of hydrological data, usually in the form of naturalized, historical monthly or daily flow records, for making environmental flow recommendations. They are based on the analysis of streamflow data and make use of the assumption that the full range of natural variability in the river's hydrologic regime is necessary to conserve river ecosystems. For this reason, the magnitude, frequency, duration, timing and rate of change of the natural flow regime are generally agreed to be the key elements central to sustaining and conserving native species and ecological integrity (Bunn & Arthington, 2002; Poff *et al*., 1997). Therefore, the hydrological methodologies consider the *hydrological regime that is needed to maintain the whole system's morphological and ecological processes* (Richter *et al*., 2011). Provided that there is a suitable daily flow data series, hydrological methods may be a reasonable approach to cover not only a basin but even larger scales (regional, national, continental). What remains challenging however is the definition of flow alteration - ecological response relationships, which – if clear and robust – may facilitate the environmental flow-setting processes towards protection and restoration. The literature review has shown that there can be strong ecological responses to flow alteration on a local basis but general, transferable quantitative relationships between flow alteration and ecological response cannot be developed (Poff *et al*. 2010). In the present article, we apply a hydrologic methodology to assess hydrologic alteration of rivers in Europe. In the absence of adequate and homogeneous ecological response data at the European scale, we cannot associate our hydrologic findings with the ecological status of rivers. Our purpose is to obtain a general view of hydrologic stress occurring, providing at a high resolution useful information for use in the determination of the required minimum river flows (ecological flows) when a complete European dataset on ecological response will become available.

2. Methods and Tools

2.1. Method of Indicators of Hydrologic Alteration (IHA) and data used

The Indicators of Hydrologic Alteration (IHA) was originally proposed by Richter *et al*. (1996) to assess the degree of hydrologic alteration caused by human intervention on rivers. The calculation of the hydrologic parameters is computed with the use of a free software tool (IHA, 2009). The IHA method was updated with a new set of hydrologic parameters (called 'E-Flow Components') (Mathews & Richter, 2007), which categorize river flows into low and high-magnitude events. As a result, there are now almost 70 hydrologic parameters (indicators) that can characterize the annual or intra- and inter-annual variability in water conditions, including the magnitude, frequency, duration, timing and rate of change of flows, Indicators are able to reflect human-induced changes and have high ecological relevance and the potential to be translated to e-flow recommendations. The implementation of the proposed IHA method at the European scale requires a continuous daily discharge dataset covering the whole Europe. This can only be achieved with the use of simulated data. We obtained gridded modelled hydrologic data by the large-scale (global) hydrologic model PCR-GLOBWB (Sutanudjaja *et al*., 2014; Van Beek and Bierkens, 2009). PCR-GLOBWB includes an online water demand scheme to estimate irrigation water requirement. Other sectoral water demands, including those from livestock, industry and household, are compiled from several sources, considering past change in population, socio-economic and technological development. PCR-GLOBWB gridded simulations were performed for two scenarios: a *near-natural* (no abstraction) run and an *anthropogenic* run (with human influence). In the *near-natural* scenario a grid-cell constitutes up to three natural land cover classes without land use/cover change throughout the simulation. For this scenario, only natural surface water bodies, e.g. rivers, wetland and lakes are considered. Reservoirs (dam constructions) are not simulated. No water demand is simulated, and, therefore, no water abstraction. On the other hand, in the *anthropogenic scenario* a grid-cell constitutes up to five land cover classes: short natural vegetation, tall natural vegetation, surface water bodies (including reservoirs), and irrigated paddy and non-paddy crop types. For this scenario, areal extents of fractions of all land cover classes change on yearly basis, particularly due to expansion of irrigated areas and progressive construction of dams/reservoirs. Water demand is simulated and, therefore, water abstraction is also simulated. By following a GIS procedure we assigned the gridded hydrologic data from PCR-GLOBWB to the 104,334 Functional Elementary Catchments (FEC) of Europe (official EU catchments (EEA, Ecrins 2016), available in the database of the project MARS (MARS, 2013)). Gridded info was transferred to FECs based on the closest neighboring distance of grid centroids and FEC outlets and verification with the use of upstream drainage areas of grids and FECs. The result of the two scenarios was two FEC-level data sets of daily discharges for a ten year period (2001-2010). One dataset represents the daily discharges for the *anthropogenic* scenario (baseline), while the second dataset represents the daily discharges of European rivers under the *near-natural* (no abstraction) scenario, when hydrologic conditions in Europe are under a status of minimal anthropogenic pressures on water from abstractions and land use modifications. By implementing the IHA method for analyzing these two hydrologic datasets we can compare the results (indicators) and derive a degree of alteration between the baseline conditions and the *near-natural* scenario, expressing proxies of pressures related to hydrologic alteration.

2.2. Calculation of Indicators of Hydrologic Alteration

Almost 70 IHA parameters were calculated based on nonparametric (percentile) statistics because of the skewed nature of most hydrologic datasets. For the calculation of some parameters the 3-, 7-, 30-, and 90-day minimums and maximums were taken from moving averages of the appropriate length calculated for every possible period that is completely within the water year. The zero flow days and base flow index parameters were also calculated. Also, reversals were calculated by dividing the hydrologic record into "rising" and "falling" periods, with the number representing the times that flow switches from one type of period to another (IHA, 2009). For the calculation of other parameters the IHA software uses an algorithm that distinguishes between high flows and low flows. Specifically, this is achieved with the use of a High flow threshold (all flows greater than the 75^{th} percentile of daily flows), a Low flow threshold (all flows less than or equal to the 50^{th} percentile of daily flows), a High flow start rate and a High flow end rate threshold. Further, part of the high flow dataset feeds the small flood and large flood sets of daily values. In order to assess the deviation of the baseline hydrologic conditions from the *near-natural* scenario we calculated the ratios between the values of the indicators for the *near-natural* scenario and the values of the indicators for the *anthropogenic* scenario (*near-natural* scenario over *anthropogenic* scenario) for all FECs. Focusing on ratios, if the value for a certain indicator is 1, it means that there is no alteration between the "anthropogenic" model run and the "near-natural" model run. If the ratio is above 1, then the value of the hydrologic indicator for the *anthropogenic* is lower than the *near-natural* scenario and the opposite.

3. Results and discussion

Hydrologic alteration across Europe can be expressed by various hydrologic indicators calculated by the IHA methodology (IHA, 2009). The produced maps consist of 104,334 FECs for which all hydrologic indicators have been calculated under both the *anthropogenic* (baseline) and *near-natural* scenario. Due to serious space limitations in this article we will present only two indicators and associated maps, the annual flow and baseflow index (BFI). A clear reduction of annual river flows has been indicated for parts of all the Mediterranean countries (Greece, Turkey, Spain, France, Italy) due to water abstractions occurring in the anthropogenic scenario. However, the average flow conditions are not influenced for the rest of Europe. The analysis shows that the total number of low flow days within the 10-y simulated period remained also unaltered for the majority of the European area, with low flow events continuing to be longer in Northern and North-eastern Europe under water abstractions and shorter in all other areas. A comprehensive baseflow index has indicated that aquifers play a key role in the streams' total flow in Central and Northern Europe, enhancing long low flow events. This situation is almost identical with the respective one under the ideal natural flow conditions. This is not the case for Southern Europe where, in large parts, groundwater abstractions, mostly for irrigation have severely reduced aquifers' water contribution to adjacent rivers and streams. Similarly to low flows, extreme low flow events are important in the North (particularly in the Scandinavian region) due to climate characteristics which enhance the prolongation of low river flow conditions. The *anthropogenic* scenario has slightly increased the duration of extreme low flow events in areas scattered across Europe. On the other hand, as low flows predominate, the total number of high flow days always covers less than the 50% of the time period and was found to remain unaltered for the largest part of the European area due to water abstractions. In contrast, alterations occur in scattered areas mostly within the Mediterranean and Balkan countries where also the frequencies of high flow events are reduced. This can also be attributed to irrigation, which reduces water availability for river flow. High flow events do not last more than a week on average in both Southern and Central Europe but are much longer in Northern Europe. Alteration is not found here except at the very local basis. A series of other hydrologic indicators and their ratios across Europe have supported the above general findings.

In Figures 1 and 2 the annual flow and the baseflow index (BFI) are shown respectively. On the right side of the figures, ratios below unity indicate increase in annual flow and BFI due to abstractions, values equal to unity show no alteration and values above unity show reduction from the natural conditions. In Figure 1 reduction is depicted on the right map with deeper colours and is observed in parts of the Mediterranean countries. Increase in flows (ratio <1) is found in Central Europe, with very large parts all across the continent and especially in the North, remaining unaltered with respect to annual river flows. The BFI is defined as: 7-day minimum flow / mean flow for year. The higher the BFI is, the greater the groundwater contribution to streamflow. The highest BFI values are observed in parts of Central Europe and Scandinavia (Fig. 2 left). The BFI has not been altered due to abstractions (Fig. 2 right) for large parts of Europe but has been decreased only in parts of the Mediterranean countries (ratio >1) due to abstractions. This is possibly connected to groundwater abstractions for irrigation which reduce the groundwater levels and the capability of aquifers to contribute with water to adjacent streams and rivers.

4. Conclusions

Hydrologic stress of European rivers can be comprehensively expressed through the calculation of the ratio (alteration) of numerous hydrologic indicators derived from time-series of daily river discharge occurring in a *near-natural* scenario without water abstractions, and time-series of discharge occurring in an *anthropogenic* (baseline) scenario with the typical water abstractions to cover needs. Mapping the hydrologic alteration on Europe's geographic background, clear trends in hydrologic stress were indicated across a North-South gradient. From the hydrologic indicators mapped, some of those, connected to low flow regimes (baseflow index, flood free season, low flow threshold), were the most informative showing that Southern Europe is more hydrologically stressed than the rest of Europe. The magnitude of river flows, the number of high flow days and the frequency of high flow events decrease in parts of the Mediterranean countries in the *anthropogenic* scenario, mostly because baseflow is significantly reduced due to abstractions. In the rest of Europe, especially the Northern part, flow temporal variations are much less pronounced, and the natural hydrologic conditions are preserved in the *anthropogenic* scenario. The GIS alteration layers with the Functional Elementary Catchment level calculations allow the identification of possible significant hydrologic stress for local areas scattered all across Europe. To be able to determine minimum ecological flows however, the water community has to associate effectively the hydrologic stress outputs of this work with known ecological response.

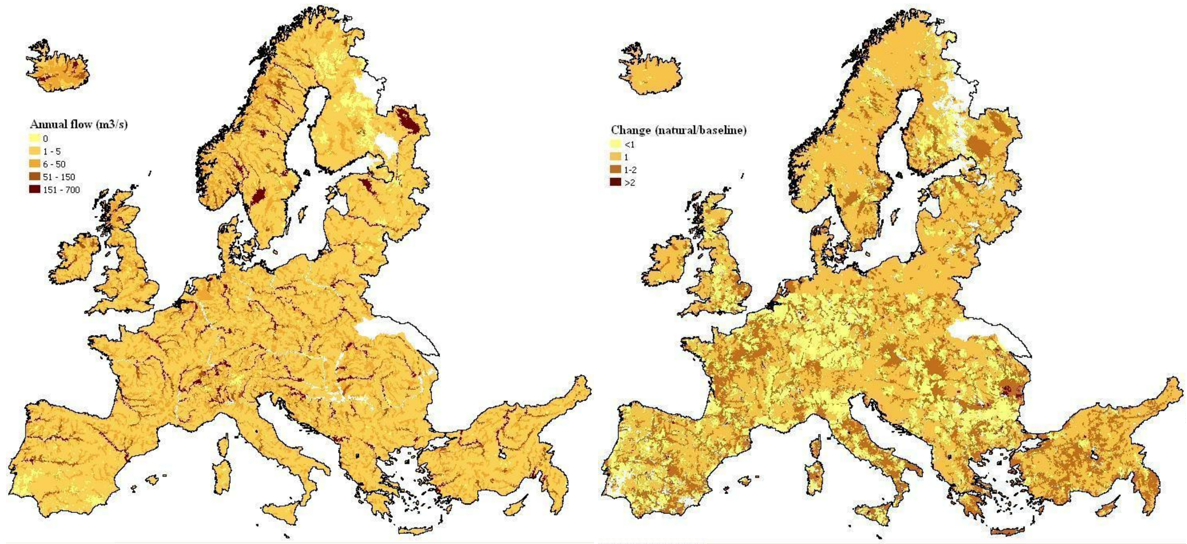

Figure 1. Left: Median annual flow (m^3/s) of the 10-y period 2001-2010 under the *anthropogenic* (baseline) scenario (water abstractions). Right: Alteration of the median annual flow from the natural conditions, expressed as median flow (natural) / median flow (baseline). Ratios below unity indicate increase in flow due to abstractions, values equal to unity show no alteration and values above unity show reduction from the *near-natural* conditions.

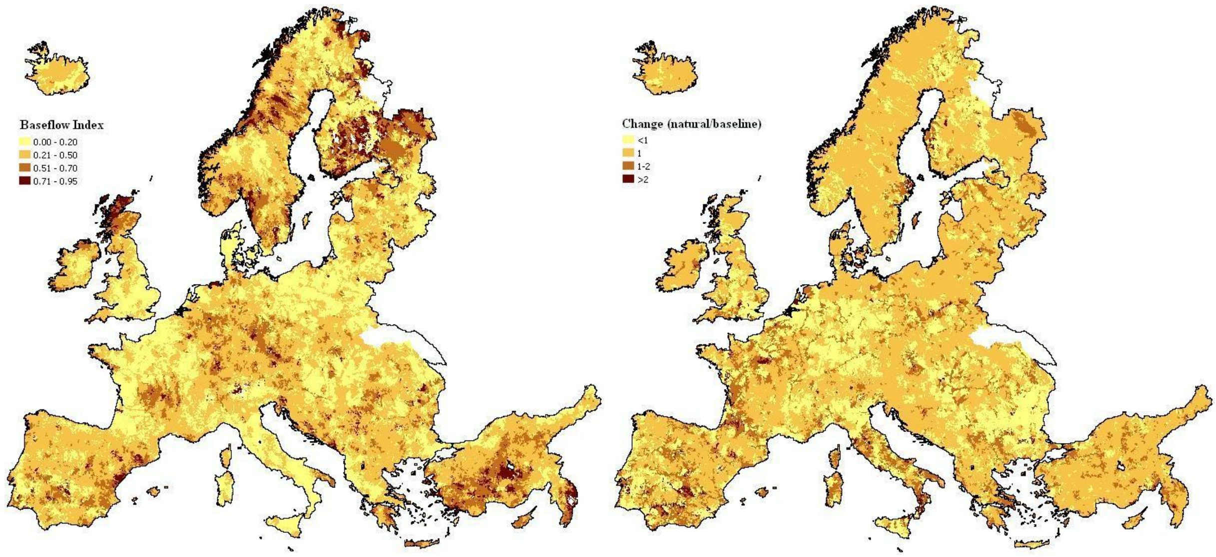

Figure 2. Left: Baseflow index (BFI) within the 10-y period 2001-2010 under the *anthropogenic* scenario (water abstractions). Right: Alteration of the BFI from the natural conditions, expressed as BFI (natural) / BFI (baseline). Ratios below unity indicate increase in BFI due to abstractions, values equal to unity show no alteration and values above unity show reduction from the *near-natural* conditions.

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