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Flow regime shifts in the Little Piney creek (US)

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ABSTRACT

Non-stationarity of climate drivers and soil-use strongly affects the hydrologic cycle, producing significant inter-annual and multi-decadal fluctuations of river flow regimes. Understanding the temporal trajectories of hydrologic regimes is a key issue for the management of freshwater ecosystems and the security of human water uses. Here, long-term changes in the seasonal flow regime of the Little Piney creek (US) are analyzed with the aid of a stochastic mechanistic approach that expresses analytically the streamflow distribution in terms of a few measurable hydroclimatic parameters, providing a basis for assessing the impact of climate and landscape modifications on water resources. Mean rainfall and streamflow rates exhibit a pronounced inter-annual variability across the last century, though in the absence of clear sustained drifts. Long-term modifications of streamflow regimes across different periods of 2 and 8 years are likewise significant. The stochastic model is able to reasonably reproduce the observed 2-years and 8-years regimes in the Little Piney creek, as well as the corresponding inter-annual variations of streamflow probability density. The study evidences that a flow regime shift occurred in the Little Piney creek during the last century, with erratic regimes typical of the 30s/40s that had been progressively replaced by persistent flow regimes featured by more dumped streamflow fluctuations. Causal drivers of regime shift are identified as the increase of the frequency of events (a byproduct of climate variability) and the decrease of recession rates (induced by a decrease of cultivated lands). The approach developed offers an objective basis for the analysis and prediction of the impact of climate/landscape change on water resources.

1. Introduction

The river flow regime identifies the natural variability of river flows [39], which is the byproduct of the stochastic fluctuations that characterize most of the hydroclimatic processes involved in the water cycle (e.g. precipitation, evapotranspiration, snow dynamics, see e.g. [32,48,50]). The inter- and intra- annual variability of river flows strongly constrain - and are in turn constrained by – anthropogenic water uses (e.g. [2,3,5,18,53,58]). Human uses like hydropower, irrigation and municipal are typically featured by high socioeconomic value, especially in arid regions where the lack of water represents a limiting factor for energy availability, food security and sanitary services. However, provided that discharges represent one of the major determinants of river habitats [16,17,31,42,43,45,52], flow diversions for human needs may conflict with the ecological uses of freshwater, whose importance for water quality and riverine biodiversity can hardly be overestimated. In fact, as the physical attributes of the stream habitat (e.g. pH, velocity, temperature) are strongly linked to the availability of river flows, modifications in the magnitude and temporal variability of streamflows can significantly constrain key ecosystem services like sediment regulation, nutrient spiraling or flood mitigation [21,24,33,40,55]. For the above reasons, the identification and classification of river flow regimes (and their long-term variability) is a fundamental task for quantifying the impact of climate change and water infrastructure development on water resources and global biodiversity (e.g. [6,10]).

Quantitatively, river flow regimes can be identified by the probability density function (pdf) of daily flows [7,8,20], that expresses the distribution of the frequencies according to which flows of different size are observed at-a-station. The streamflow pdf (hereafter termed streamflow distribution) provides the same information of the flow duration curve, which represents the percentage of time during which a given flow is equaled or exceeded [54]. Streamflow distributions and flow duration curves quantitatively describe the magnitude of discharge fluctuations and the frequency of low and high flows [14]. Besides purely graphical techniques [51], methods for predicting streamflow distributions and flow duration curves can be broadly grouped in two categories: statistical and process-based methods. Statistical methods are typically aimed

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at the estimate of flow duration curves at sites where only a limited amount of information (or no information at all) is available, exploiting the concept of hydrological similarity among catchments (e.g. [4]). These methods can be parametric, implying that the parameters of the flow duration curve are related to physical attributes of the contributing catchments (see e.g. 11,12) or non-parametric, thereby requiring the definition of representative dimensionless (i.e., scaled) duration curves [25]. Physically based approach, instead, derive the properties of the streamflow distribution by explicitly incorporating some physical processes involved in rainfall-runoff transformation, like e.g. precipitation or soil moisture dynamics (e.g. 6,13,46,56,57). Physically based approaches have the advantage of setting causal relationships between drivers and response, thereby allowing deeper insight on the impact of climate change and soil-use modifications on flow regimes. Among the diverse physically-based approaches existing in the literature, this paper is based on the stochastic analytical model developed by Botter et al. [7], which is a mechanistic model where streamflow dynamics are driven by a catchment-scale soil–water balance forced by stochastic rainfall. The model allows the streamflow distribution to be analytically expressed in terms of three measurable parameters that summarize key landscape and climatic attributes.

Climate variables (e.g. precipitation, temperature) are known to be highly non stationary [36]. This lack of stationarity is the byproduct of the interaction between causal and stochastic components in global-scale circulation processes (e.g. [37]), including sustained drifts possibly enhanced by anthropogenic drivers [1]. Similarly, landscapes are ever-changing entities, due to the dynamical response of soil and vegetation properties to external environmental drivers [28,49] and change in soil use implied by urbanization, deforestation and cropping (see e.g. [26]). Non-stationarity of climate drivers, soil-use and soil-cover is propagated through the whole hydrologic cycle, producing significant inter-annual and multi-decadal fluctuations of hydrologic regimes [6]. As a consequence, streamflow distributions need to be conceived in a dynamical way (i.e., as time-variant distributions). Understanding the temporal trajectories of river flow regimes is of critical importance for the management of freshwater ecosystems and the security of human water uses in times of global change.

With the above premises, this paper aims at quantifying the temporal trajectories of seasonal flow regimes in the Little Piney creek (a tributary of the Mississipi Missouri river, Section 2.1). To that aim, the streamflow distribution is theoretically linked to some relevant climatic and landscape attributes by means of the stochastic approach proposed by [7] (Sections 2.2 and 2.3). The stochastic model offers a basis to analyze the relationship between the inter-annual change of seasonal hydrologic regimes and the underlying modification of climate/landscape features (Sections 2.4). The results of the application to the Little Piney creek are presented in Section 3, where the temporal patterns of a set of hydrologically meaningful variables are discussed. These hydrological variables include: (i) mean water budget; (ii) frequency/intensity and response time of flow-producing events; and (iii) seasonal streamflow distributions. A set of conclusions closes then the paper.

2. Material and methods

2.1. The Little Piney creek(MO)

The Little Piney creek is a small river located in the Midwest of the United States within the Ozark Plateaus (MO) (Fig. 1). It has been selected as a case study because of the long-term availability

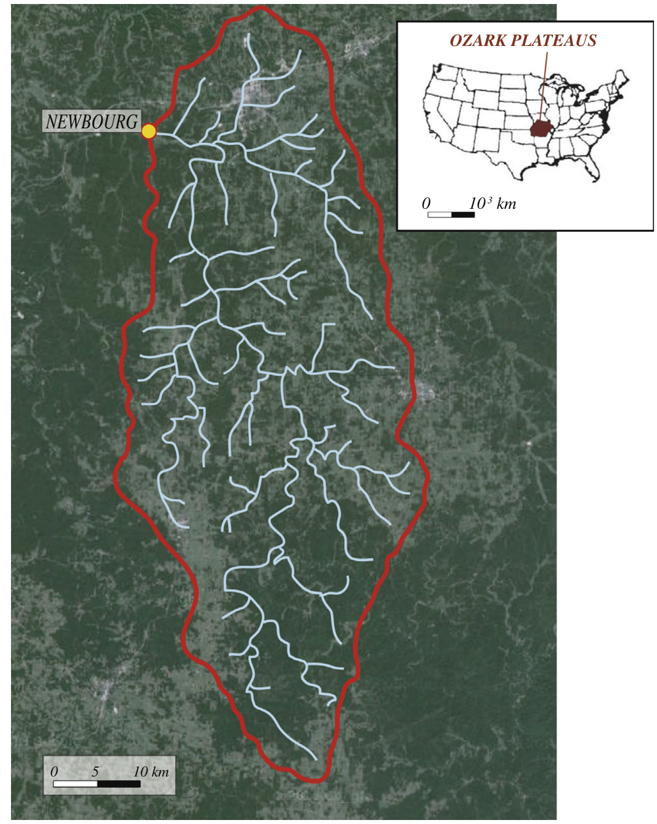

Fig. 1. Contributing catchment and stream network of the Little Piney creek at the outlet of Newburg. The inset shows the location of the Orzak Plateaus (where the study catchment is located) within the United States.

of hydroclimatic data and the complex history of land use change, which offers a unique opportunity to analyze the influence of climate and landscape change on river flow regimes. The Little Piney creek flows into the Gasconade river, which is an important tributary of the Missisipi–Missouri. The contributing area at the selected outlet of Newburg (37°91′75″N, 91°90′11″W) is 510 km^2. The average altitude of the catchment is about 210 m *a.s.l.*, and the slope of the terrain is typically gentle, with a maximum relief below 300 m. The climate of the region is temperate, with a relatively low mean annual precipitation (typically from 1000 to 1200 mm/year), unevenly distributed across the seasons and with a negligible contribution of solid precipitation. The annual average of the air temperature is about 17 °C. The geologic structure of the region is quite complex, with a patchy distribution of Roubidoux rock formations, Gasconade Dolomites and loesses underlying an organic vegetated soil with variable depth. A fault line crosses the main course of the Piney creek at Hickory Point. The river has a meandering gravel-bed main course, frequently feeded by a brunch of intermittent tributaries. A quite uniform water supply is contributed to the main river in correspondence of the Piney and Lane springs, located in correspondence of the middle part of the river course. The mean discharge during the last 90 years is about 4.5 m^3/s, with a maximum recorded flow close to 920 m^3/s (December 1982).

The landscape of the Little Piney creek is quite pristine (Fig. 1): forests and grassland are the dominant soil uses in the entire region, and there is a reduced percentage of urbanized soils [19]. The region of the Ozarks, where the catchment is located, has a complex history of land use change and variable degrees of anthropogenic pressure [23], whose effect on the river hydrochemestry and geomorphology has been documented by several previous