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River flow regimes and vegetation dynamics along a river transect

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ABSTRACT

Ecohydrological processes occurring within fluvial landscapes are strongly affected by natural streamflow variability. In this work the patterns of vegetation biomass in two rivers characterized by contrasting flow regimes were investigated by means of a comprehensive stochastic model which explicitly couples catchment-scale hydroclimatic processes, morphologic attributes of the river transect and in-stream bio-ecological features. The hydrologic forcing is characterized by the probability distribution (pdf) of streamflows and stages resulting from stochastic precipitation dynamics, rainfall-runoff transformation and reach scale morphologic attributes. The model proved able to reproduce the observed pdf of river flows and stages, as well as the pattern of exposure/inundation along the river transect in both regimes. Our results suggest that in persistent regimes characterized by reduced streamflow variability, mean vegetation biomass is chiefly controlled by the pattern of groundwater availability along the transect, leading to a marked transition between aquatic and terrestrial environments. Conversely, erratic regimes ensure wider aquatic–terrestrial zones in which optimal elevation ranges for species with different sensitivity to flooding and access to groundwater are separated. Patterns of mean biomass in erratic regimes were found to be more sensitive to changes in the underlying hydroclimatic conditions, notwithstanding the reduced responsiveness of the corresponding flow regimes. The framework developed highlights the important role played by streamflow regimes in shaping riverine environments, and may eventually contribute to identifying the influence of landscape, climate and morphologic features on in-stream ecological dynamics.

1. Introduction

Natural streamflow variability is currently recognized as a major driver for most processes occurring in fluvial landscapes. The whole range of streamflows, their temporal fluctuations and their interactions with groundwater contribute to the determination of form and functioning of riverine ecosystems [34,46,54]. The study of interconnections among hydrological and biological dynamics has gained importance in recent years (e.g. [22,23,30,48,51,52,58]) because of the increasing awareness of the interconnected role of these processes in preserving and restoring healthy environments necessary for the provision of humanly valued ecosystem services.

In fluvial environments, one important focus is on the riparian vegetation dynamics at the reach scale. Streamflow variability plays a crucial role in the dynamics of riparian plant communities and the associated ecological processes [1,40,59]. In particular, flooding and groundwater availability are key controls in riparian vegetation dynamics [3,13,25,33,35,42]. The state of flooding is characterized as the duration of time when a point along the river transect is inundated by the stream. Flooding can affect riparian vegetation both in a positive (providing nutrients, moisture and seeds) and a negative (uprooting, sediment removal, anoxia, and burial) manner (for more details on the impact of flooding on vegetation see [21,24,29,38,39,41,61]). However, the detrimental impacts of flooding are more severe and typically outweigh potential beneficial effects. In contrast, when the point is exposed, vegetation (in particular phreatophyte species) can grow by accessing groundwater which fluctuates in correlation with streamflows. Therefore, the dynamics of riparian vegetation along a river transect is closely connected to the stochasticity of streamflows, which is in turn controlled by landscape, climate and morphologic features of the river and the contributing catchment.

The temporal variability of streamflows is typically described by means of the probability density function (pdf) of daily discharges, or the related flow duration curve [16,20,53,60]. The prediction and characterization of streamflow distributions has

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been the goal of a large number of hydrologic studies which are based on statistical methods or process-based (numerical and analytical) models [60,62]. Recently, a stochastic analytical framework for linking the features of the streamflow distribution to climate and landscape attributes has been proposed [5,8,9]. This framework allows for a quantitative distinction between two different types of flow regimes (termed persistent and erratic), based on the ratio between mean inter-arrival of flow-producing rainfall events and the mean catchment response time [12]. Persistent regimes are characterized by a small range of streamflows (reduced variability), while erratic regimes are characterized by a wider range of streamflows (enhanced variability) that results from the alternation between intense floods and prolonged droughts.

The impact of the stochastic fluctuations of streamflow on the dynamics of riparian vegetation has been previously explored. Camporeale and Ridolfi [14] presented the most comprehensive process-based stochastic model of riparian vegetation dynamics and investigated the role of flow variability in vegetation distribution along a riparian transect through modeling the hydrological noise as dichotomic noise. Camporeale and Ridolfi [15] further developed the model to investigate the effect of hydrological fluctuations on noise-induced stability and bi-modality in vegetation biomass dynamics along a riparian transect. This model was extended to investigate the scaling of the riparian width at watersheds scale by Muneepeerakul et al. [37], and utilized by Perona et al. [43] to investigate riparian vegetation dynamics in meandering and braided rivers. Perona et al. [42] developed a stochastic approach for studying sediment-vegetation dynamics driven by stochastic flood disturbances at a flood plain scale. Tealdi et al. [56] explored the effects of dam induced hydrological changes on total biomass along the transect. [18] developed a rigorous stochastic description of growth-uprooting that was validated through a flume experiment [44]. More recently, Tealdi et al. [57] investigated the role of the interspecific interactions, driven by a shot-noise hydrologic driver, on the distribution of the species along a river transect.

Here the approach of Camporeale and Ridolfi [14] is adopted and, for the first time, complemented with the stochastic model of streamflows and stages developed by Botter et al. [5,11], with the goal of analyzing the signature of catchment-scale hydroclimatic processes and river flow regimes in the patterns of vegetation biomass. The model is then applied to two catchments with opposing flow regimes: (i) the Boite, located in north eastern Italy (persistent), and (ii) the Youghiogheny, in MD USA (erratic). A detailed process-based analysis of the role played by hydrologic variability as the driver and limiting factor for vegetation growth along a river transect is presented. The main elements of novelty with respect to previous works are: a rigorous analytic formulation for the probability and mean duration of inundation/exposure, explicitly based on the climatic and hydrologic parameters is provided and validated against field data; based on this framework, the correlation scale of the hydrologic noise is properly defined such that it changes along the river transect according to the underlying flow variability rather than being assumed to be constant as in previous studies [14]. The relative role of flooding and groundwater access in mean vegetation biomass is then explored through an analytic index that quantifies the deviation from carrying capacity. The impact of long-term variability of climate on the mean vegetation biomass along the transect is analyzed.

2. Model outline

A general representation of the ecohydrological processes driving the riparian vegetation dynamics is depicted in Fig. B.1, which presents the temporal variation of streamflows, stages and vegetation biomass (left) and the associated pdf for each variable (right). The stochastic fluctuation of the streamflows is controlled by climatic and landscape features of the contributing watershed (expressed by the pdf of streamflows). The temporal variability of river stages is, in turn, a mirror of these fluctuations since they result from the random sequence of flow pulses delivered from the contributing catchment, suitably modulated by the morphological features of the transect. For a given point, vegetation biomass alternates between growth (when the site is exposed) and decay (when the site is inundated). The length of the exposure/inundation time as well as vegetation specific features determine the extent of growth and decay. We can therefore express the dynamics of vegetation along a river transect by means of coupling catchment-scale hydroclimatic processes, morphologic attributes of the river transect and vegetation specific biological features. In this section we outline the analytical frame work utilized to model these processes.

The flow regime defines the river flow variability and is embodied by the streamflow pdf. Here, the flow regime is characterized by means of a recent analytical mechanistic model [5] based on a catchment-scale soil water balance forced by stochastic rainfall which is modeled (at daily timescales) as a marked Poisson process with frequency λ_p and exponentially distributed depths with average α [5,47,50]. Accordingly, the specific (per unit catchment area) streamflow (Q) is composed of instantaneous jumps corresponding to rainfall events filling the soil water deficit in the root zone (taking place with frequency $\lambda < \lambda_p$) and the exponential decays between them. Therefore, the stochastic temporal dynamics of Q at a daily timescale (Fig. B.1(a)) can be described as:

$$\frac{dQ(t)}{dt} = -K_T Q(t) + \xi_Q(t) \tag{1}$$

where the first term on the right-hand side represents the deterministic exponential decay of Q between events (with rate K_T) and the second term represents the stochastic jumps induced by streamflow producing rainfall events (Fig. B.1(a)). The inter-arrival time of events and the jumps themselves are exponentially distributed, with means $1/\lambda$ and α respectively. The resulting pdf of specific streamflows (Fig. B.1(b)) is expressed by a Gamma distribution [5]:

$$p_q(Q) = \frac{\Gamma\left(\frac{\lambda}{K_T}\right)^{-1}}{\alpha K_T}\left(\frac{Q}{\alpha K_T}\right)^{\frac{\lambda}{K_T}-1} \exp\left(-\frac{Q}{\alpha K_T}\right) \tag{2}$$

where Γ is the complete gamma function (see Appendix A for more details on the model). According to Eq. (2), the coefficient of variation of Q is given by $CV_Q = \sqrt{\frac{K_T}{\lambda}}$, thereby allowing the identification of two distinct regimes: when $\lambda > K_T$ the frequency of the events contributing to streamflow is large compared to the recession time scale and $CV_Q < 1$, implying that the flow variability is reduced (persistent regime). Conversely, when $\lambda < K_T$ the frequency of flow-producing events is small and $CV_Q > 1$, meaning that the flow variability is enhanced (erratic regime).

The stochastic fluctuations of Q control the temporal variability of stage h. The functional relationship between streamflow Q and stage h (above a certain datum h_0), for a fixed cross section, is usually estimated through a power law relationship $h = aQ^b$ (otherwise known as the discharge rating curve) where a and b are dependent on the cross section morphology [17,32,55]. The stochastic temporal dynamics of h at a daily timescale (Fig. B.1(c)) can therefore be derived from the Eq. (1) as:

$$\frac{dh(t)}{dt} = -bK_T h(t) + \xi_h(t) \tag{3}$$

Much like the streamflows, here the first term on the right-hand side represents the deterministic exponential decay of h between