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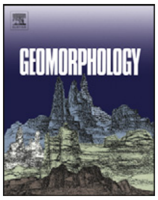

A neutral model as a null hypothesis test for river network sinuosity

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ABSTRACT

Neutral models (NMs) are built to test null hypotheses and to detect properties at work in an object or a system. While several studies in geomorphology have used NMs without explicitly mentioning them or describing how they were built, it must be recognized that neutral models more often concerned theoretical explorations that drove such use. In this paper, we propose a panel of NMs of river (channel) networks based on a well-established relationship between observed and simulated sinuosity properties. We first simulated new instances of river networks with a (one-parameter) neutral model based on optimal channel networks (OCN) and leading to homogeneous sinuosity watersheds. We then proposed a "less neutral" model able to generate a variety of river networks accounting for the spatial heterogeneity of observed properties such as elevation. These models, providing confidence levels, allowed us to certify that some properties played a role in the generation of the observed network. Finally, we demonstrated and illustrated both models on the Bidasoa watershed (Spain–France frontier), with a new dedicated software (called SSM). NMs in geomorphology ensure to progressively help to identify the process operating in an observed object, and to ultimately improve our understanding of it (i.e. intrinsic need). But they also provide simulated samples statistically "similar" to an observed one, thus offering new alternatives to every process carried by the observed object (i.e. extrinsic need). Artificial river networks studied here would be of great value to environmental sciences studying geomorphology and freshwater-related processes.

1. Introduction

Environmental sciences use every day more and more *null hypothesis* and *neutral models* to test their working hypotheses. The inherent stochasticity of our world adds a varying amount of noise to every phenomenon, thus blurring it (Frank, 2009). A simple and easy-to-manage method to detect the process at work behind the noise consists in formulating the working hypothesis that the studied process is present and could be statistically discriminated from a purely random mechanism. Such a method of searching for a hidden mechanism is the common way of testing (invalidating) the null hypothesis defined by: "the process is random" (Fisher, 1966). When the studied object is complex enough so that it cannot be summarized into a set of values (e.g. spatial objects), we need to use a neutral model (NM) to test whether the observed pattern is unlikely to emerge by chance. Hence, an NM is a model that avoids a process supposed to generate the studied object or phenomenon, and tests whether it is sufficient to generate it or not (Nitecki and Hoffman, 1987). When the NM is invalidated (i.e. rejected or falsified), it reinforces our belief that the mechanism being studied is at work, although this is not a proof. In this study, we aim at defining several neutral models of river (channel) networks, powerful enough to test a wide range of geomorphologic processes.

Physics has been using NMs for a long time (Fisher, 1966). It rapidly became common, and meaningful, to use NMs to test hypotheses, as chance is ubiquitous in physical processes, and as there exists a huge amount of data provided by physical instruments and sensors. Conversely, the growing use of NMs in environmental and living sciences in recent decades is a clear departure from past practices (Nitecki and Hoffman, 1987). Maybe due to the observation of the important role played by chance in life too, neutral models recently flourished in studies of biological and ecological mechanisms. As a non-exhaustive list, we may cite the neutral genetic theory (Kimura, 1983), the neutral-community theory (Hubbell, 2001), the Lévy walks (Viswanathan et al., 1999), or the landscape-neutral models (Gardner et al., 1987). For example, landscape-neutral models have been developed to simulate landscape (land use and land cover) structures and landscape functioning without explicitly using the processes and rules supposed to drive such landscapes (Gardner et al., 1987; Gaucherel et al., 2006; Gaucherel, 2011). We argue here that such neutral models would be also relevant to test a wide range of geomorphological hypotheses.

We sometimes have the intuition that a river network feature is caused by some of the substrate properties, such as a geologic fault or a relief feature. How to build a river network neutral model to test this

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hypothesis? Would chance be able to generate this precisely observed network feature? To answer this question, you would need to build a null-hypothesis and its associated NMs, largely using random functions, to test whether chance can statistically lead to the observed configuration or not. Scrutinizing the literature in geomorphology reveals that several studies have explored related questions, without explicitly mentioning NMs (Orlowski et al., 1993; Robert and Roy, 1993; Aubry and Piegay, 2001; Zender et al., 2003; Hung and Wang, 2005; Lewis et al., 2006).

The simplest river network NM may be built by randomly directional connecting a set of links, while ensuring at the same time that no loops, multiple bifurcations or other non- realistic features appear on the downstream flow. Neutrality in an NM is a gradual property in the sense that it is possible to adjust the role played by chance to suit the requirements of the study. By relaxing the neutrality constraint, it is possible to model less neutral river networks. Such an adjustment was proposed and extensively explored some years ago with the optimal channel network (OCN) models (Rigon et al., 1993; Rodriguez-Iturbe and Rinaldo, 1997). The authors demonstrated how it is possible to model realistic river networks with a parsimonious (sometimes one-parameter) NM, and theoretically utilize these network properties to improve our understanding of network generation. However, we should keep in mind that an OCN focused on two complementary properties: the sinuosity and the dendritic pattern inherent to all river networks. Many other network NMs may be defined on the basis of other network properties to address other questions (Karlinger and Troutman, 1992; Sinclair and Ball, 1996; Baas, 2002).

Although powerful OCNs do exist, they lack a property that is important for our purpose: the *link* with an observed system. Indeed, it is one thing to generate new river networks, and quite another to generate a network resembling an observed one. It is the objective of this paper to develop a methodology aiming at mimicking a real river network with the help of more or less neutral models. For this purpose, we established a link between observed and simulated sinuosities in a previous paper (Gaucherel et al., 2011). Our working hypothesis states that it is possible to build a variety of NMs and to ultimately use them as confidence levels to detect the significant features of an observed network. Our main assumption was that every river network may be characterized by its sinuosity and dendritic pattern (Rodriguez-Iturbe and Rinaldo, 1997). This point will be discussed later in the text.

We intend to proceed gradually, in a kind of incremental hypothetico-deductive approach. We will first simulate instances of river networks with a (one-parameter) NM leading to homogeneous sinuosity watersheds. We will then propose a less neutral NM able to generate a variety of river networks accounting for the spatial heterogeneity of observed properties. These models, providing confidence levels, will allow us to certify that the properties play a role in the generation of the observed network. Finally, we demonstrate and illustrate this in the case of the Bidasoa watershed located at ca. 43°22′N and 1°47′W partly defining the frontier between Spain and France, from the Endarlatsa village located 13 km before its outlet. The Bidasoa basin we studied here has an area of 672 km^2, with a maximal elevation equal to 1400 m and a total river length of 855 km. We performed these simulations with a new dedicated software (called SSM, for self-similar model), so that other studies would benefit from the same methodology.

2. Materials and methods

2.1. State-of-the-art of neutral models for river networks

The principle behind every river network is to drain the rainfall water collected over the whole watershed to its unique outlet. This may basically be achieved by a drainage pattern more or less dendritic (in terms of the number of connected links), with local patterns more or less sinuous (i.e. straight or curvilinear links). This is the objective of OCNs, namely to model various samples of river networks on the basis of such a sinuous/dendritic property (Rigon et al., 1993; Rinaldo et al., 1993; Rodriguez-Iturbe and Rinaldo, 1997). One strength of the OCN model is that it can control this dominant property on the basis of a single parameter defining the function which characterizes the river network pattern: the parameter γ, ranging from 0 for highly sinuous patterns, to unity for highly dendritic and directed patterns. This function synthesizing the system dynamics is called the *Hamiltonian*, in reference to the energy function that has helped physics to reformulate classical mechanics with a new mathematical formalism. The various OCN models proposed by the previous authors are NMs, as they use a stochastic generation of links, without invoking specific physical mechanisms to build the network. As our NM will be partly based on the OCN, we briefly detail here their principle.

The adjective “neutral” does not mean that these models do not have any physical foundations, but, in a sense, they remain phenomenological (Gaucherel, 2011). In hydrographical systems, the observed power-law distributions of discharge mass are closely linked to energy dissipation within the river basin (Rodriguez-Iturbe et al., 1992; Rinaldo et al., 1993). The total cumulative area draining into a river link is used in these works as a surrogate variable for discharge and presents a self-similar behaviour indeed observed in real river basins. This scaling behaviour, often measured in natural drainage networks, reflects a preferential spatial aggregation (i.e. a topology) leading to dendritic patterns. These authors used the exceedence probability of the drainage area characterizing the self-similar topology of the hydrographical network to build a Hamiltonian for their system (Rinaldo et al., 1993; Rodriguez-Iturbe and Rinaldo, 1997):

$$H_{OCN} = \Sigma_i (A_i)^{\gamma} \tag{1}$$

where A_i denotes the total contributing drainage area at a point i of the network, and γ the coefficient linking the local geometry to the global topology of the network. The value of γ used in their studies is often close to 0.5, which comes from simple hydrodynamic considerations. In their works, the authors suggest that minimization of the Hamiltonian should be the leading principle for finding stable river networks (i.e., OCNs), with a remarkable degree of success: the observed excess probability of drainage areas, after minimization, is a decreasing power-law with exponent 0.45, in agreement with real river networks. Other models could have been used for this purpose (Karlinger and Troutman, 1992; Sinclair and Ball, 1996; Baas, 2002; Hung and Wang, 2005), but the OCN approach is, to our knowledge and experience, a parsimonious and robust one to study and simulate realistic river networks.

OCNs have been developed to address quite theoretical questions, far from the objective to mimic (to reproduce) a specific observed river network. An NM dedicated to river networks with this aim should first focus on a relevant network property and then try to model it without invoking the process (or processes) supposedly at work. Mere rigorous computing of the averaged sinuosity of a network does not allow one to grasp all of its complexity. Because river networks are self-similar, we need at least a multiscale scalar to capture its dominant property: indeed, many models among which OCNs have proven that natural river networks adopt an optimized pattern in between a fully dendritic pattern and a fully sinuous pattern.

On the basis of this sinuous/dendritic property, we now ask: Is our observed network specific, or could it have been generated by chance? In other words, how contingent is it? In order to have an answer, we need a network NM to demonstrate by a null-hypothesis test how different this object is from random networks. In addition, the NM should model the network with the most parsimonious information (i.e. using random distributions and very few parameters); otherwise several processes would have to be taken into account (Gaucherel et al., 2006; Gaucherel, 2011). Now how to accurately mimic this observed river network, without simulating a large number of networks, and selecting the one most similar? The most efficient way to proceed consists in