Geomorphology 214 (2014) 148–156

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Simulation of braided river elevation model time series with multiple-point statistics

Guillaume Pirot *, Julien Straubhaar, Philippe Renard

Centre for Hydrogeology and Geothermics, University of Neuchâtel, rue Emile Argand 11, CH-2000 Neuchâtel, Switzerland

ARTICLE INFO

Article history:
Received 30 July 2013
Received in revised form 24 January 2014
Accepted 28 January 2014
Available online 13 February 2014

Keywords:
Braided river
Topography
Modeling
Digital elevation model
Multiple-point statistics
Time-series

ABSTRACT

A new method is proposed to generate successive topographies in a braided river system. Indeed, braided river morphology models are a key factor influencing river–aquifer interactions and have repercussions in ecosystems, flood risk or water management. It is essentially based on multivariate multiple-point statistics simulations and digital elevation models as training data sets. On the one hand, airborne photography and LIDAR acquired at successive time steps have contributed to a better understanding of the geomorphological processes although the available data are sparse over time and river scales. On the other hand, geostatistics provide simulation tools for multiple and continuous variables, which allow the exploration of the uncertainty of many assumption scenarios. Illustration of the approach demonstrates the ability of multiple-point statistics to produce realistic topographies from the information provided by digital elevation models at two time steps.

1. Introduction

Braided rivers constitute an important part of alluvial systems in alpine regions such as Switzerland. Many of these rivers were channelized in the past and are now targeted by restoration projects (Glenz, 2013) for flood prevention, water management purposes, biodiversity preservation, and leisure activities (FOEN, 2009; Peter, 2009), particularly in the context of climate change (Macklin and Rumsby, 2007). As a result of the erosion and deposition processes, the morphology of braided rivers is a signature of such active systems. Morphology is a key parameter, first toward the understanding of dependent ecosystems (Amoros and Bornette, 2002; Richards et al., 2002; Clarke et al., 2003; Van Der Nat et al., 2003; Tockner et al., 2009), and also to better understand the main geological structures of the resulting aquifers in order to study groundwater flow and transport (Thomas and Nicholas, 2002; Käser et al., in press), or surface and subsurface relationships. In a hydrogeological context, simulations of successive morphologies could also be used to produce three-dimensional heterogeneous geological models. These issues are not addressed in this paper but they justify the need of topography models. The purpose of this work is to present a new way of modeling braided river topography and its evolution.

Static models of braided river morphology can be achieved by LIDAR data acquisition followed by image processing (Westaway et al., 2003) and analyses can be derived from descriptive methods characterizing the length scale and the main topographic structures (Rust, 1972; Miall, 1977; Germanoski and Schumm, 1993; Goff and Ashmore, 1994; Warburton and Davies, 1994; Foufoula-Georgiou and Sapozhnikov, 2001; Hundey and Ashmore, 2009; Lane, 2009). But these approaches are often limited to a single time step (static aspect) and restrained to the area of acquired data.

Simulations based on process imitating methods such as cellular automata models (Murray and Paola, 1994; Nicholas et al., 2009) or such as event-based models (Pyrcz et al., 2009), which can be validated by comparisons to laboratory experiments (Ashmore, 1982), allow for models of the system over successive time steps. Nevertheless, the conditioning to field measurements such as borehole data is often very difficult. To overcome this drawback, an alternative is the use of MPS simulations. These techniques are nonparametric and allow for the reproduction of complex spatial features from a conceptual model called training image (TI), as well as to account for conditioning to field data. To our knowledge, multiple-point statistics (MPS) has not yet been used to simulate successive braided river morphologies. MPS has been introduced by Guardiano and Srivastava (1993), and first practical algorithms such as SNESIM (Strebelle, 2002) were designed for the simulation of categorical variables. The algorithm proposed by Mariethoz et al. (2010), the direct sampling (DS), is much more flexible and can deal with joint simulations of multiple categorical and continuous variables. Because the DS method can reproduce spatial structures and complex correlations between several continuous variables (Mariethoz et al., 2012), this algorithm allows for simulations of successive digital elevation models (DEMs).

* Corresponding author. Tel.: +41 32 718 26 07.
E-mail address: guillaume.pirot@unine.ch (G. Pirot).

http://dx.doi.org/10.1016/j.geomorph.2014.01.022
0169-555X/

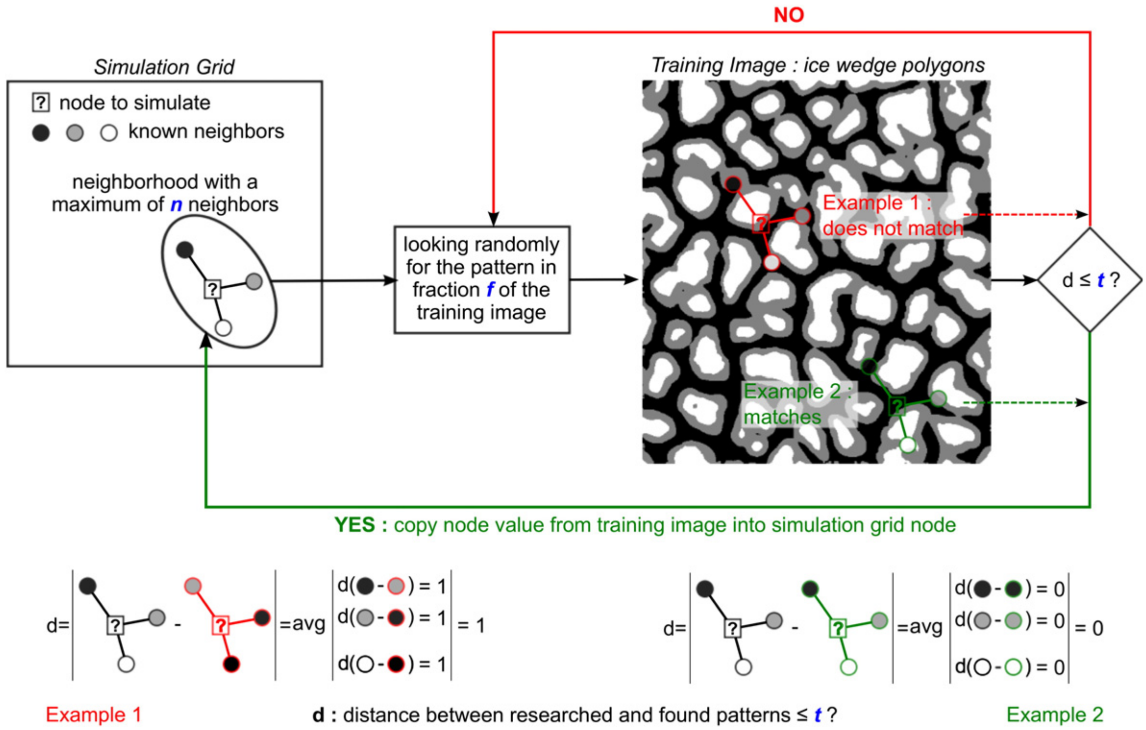

Fig. 1. Workflow of DS.
Courtesy of Meerschman et al. (2013).

Following those ideas, in this paper, the principle of a new method to simulate braided river topographies at successive time steps is proposed. It combines the advantages of the DS algorithm, with the large-scale data available from LIDAR topography. The approach is illustrated with statistical simulations of topography time series. The training datasets (TIs) are based on successive DEMs of the Waimakariri River, New Zealand (Lane et al., 2003) acquired with LIDAR at four time steps.

The paper is structured as follows. The DS algorithm is briefly presented in Section 2. The simulation of DEM time series with MPS algorithms is not straightforward, mainly because of large scale heterogeneities and trends in the TIs. Therefore Section 3 describes first a data analysis of the available TIs. That leads us to propose a methodology making use of auxiliary variables to enable realistic simulations of successive DEMs, with respect to the observed nonstationarities present in sparse training data sets. The method is detailed and demonstrated within Section 4. The paper ends with a statistical validation of the simulations in Section 5.

2. The direct sampling, an MPS algorithm

Multiple-point statistics (MPS) algorithms allow us to simulate a random function Z on a domain called the simulation grid. The random function spatial statistics are retrieved from a conceptual model known as TI. In the TI, Z is known over its entire domain (Fig. 1).

Each pixel of the simulation grid is simulated sequentially, one after another. A random path visiting every node in the simulation grid is defined, and each location $\mathbf{x}$ in the path is successively simulated as follows. The data event $\mathbf{d}(\mathbf{x})$ is the pattern constituted by the spatial ensemble of known values $Z(\mathbf{x}+\mathbf{h_i})$ in the neighborhood of $\mathbf{x}$ ($\mathbf{h_i}$ being a lag vector), i.e., the conditioning data and the already simulated points. Then, the value $Z(\mathbf{x})$ to simulate at location $\mathbf{x}$ is drawn from the cumulative distribution function F conditionally to the local data event $\mathbf{d}(\mathbf{x})$: $F(z,\mathbf{x},\mathbf{d}(\mathbf{x})) = \mathrm{Prob}\{Z(\mathbf{x}) \leq \mathbf{z}|\mathbf{d}(\mathbf{x})\}$. F is derived from a similar local data event present in the TI. F can be dealt with in two ways.

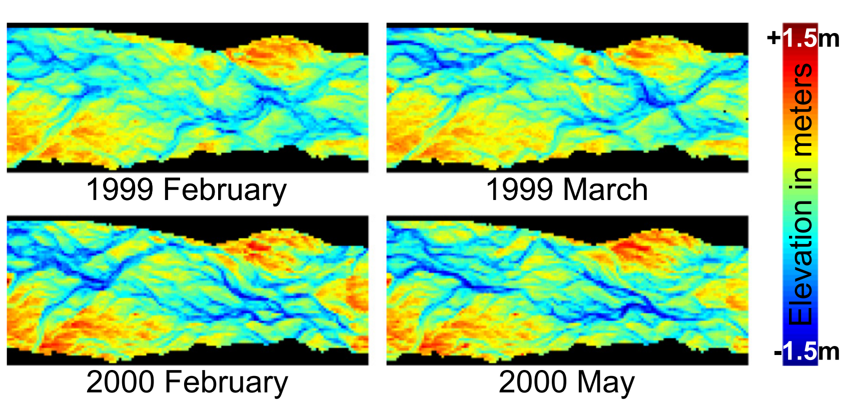

Fig. 2. 2,900 m × 1,200 m (145 pixels × 60 pixels — x axis × y axis) DEMs of the Waimakariri River, New Zealand at four time steps. Red: highest elevations; blue: lowest elevations.