Simulating braided river aquifer heterogeneity using a pseudo-genetic approach and multiple-points geostatistics

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Abstract In this work, we propose a new method to model the heterogeneity of braided river deposits. It combines high resolution analog data with the use of the Direct Sampling method embedded in a pseudo-genetic algorithm. On the one hand, we use high resolution Digital Elevation Models obtained from Airborne photography and LIDAR acquired at successive time steps on analog sites. These data provide both high resolution and large scale information. On the other hand, the Direct Sampling algorithm is a recent multiple points statistics method allowing to work directly with continuous variables. Here the training images represent topography variations due to erosion and deposition processes on a time interval. Successive topography surfaces are built by iterative simulations conditional to the previous time steps. The over-lapping and crossing surfaces produce volumes that are populated by different sedimentary textures and structures, according to the sedimentary raw material, volume shapes and analog outcrops.

Introduction

Braided river systems are characteristic of high energy environments which result in highly heterogeneous deposits. In Alpine regions such as Switzerland, they constitute an important part of the alluvial aquifers which are taped for drinking water

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supply. To model the heterogeneity of such deposits, several 3D sedimentary model set up exist. Among them, descriptive methods translating geological or geophysical site-specific data into conceptual facies models or structure imitating methods including a wider variety of stochastic models exist but do not include strong geological conceptual knowledge and their degree of realism is rather weak. Another way of modeling those environments is to use process imitating methods, but the conditioning to field data is often very difficult.

The Direct Sampling (DS) algorithm [6] is a recent Multiple Points Statistic (MPS) method dealing as well with continuous variables as with categorical variables. As all MPS techniques it allows to generate realistic patterns from the search in the Training Image (TI). Another advantage of the algorithm is its ability to easily condition simulations by field data. This is why the DS algorithm is fit for our purpose of modeling heterogeneous deposits. A crucial issue is its requirement for TIs. A possibility can be to draw manually TIs, another to use object based models to generate TIs, but the realism of the TIs may then be subject to controversy. In our case we can be confident in the realism of the TIs as we use Digital Elavation Models (DEMs) of the Waimakariri river [5] obtained from LIDAR topography at different timesteps to simulate topographies and in a second part we use a fine scale 3D model of the Herten gravel site [3, 1] obtained from successive close outcrops to generate facies. As it is not possible to have access to outcrops (inactive riverbed) and to observe topography evolution (active riverbed) simultaneously, it explains why we have to rely on two analog data sources.

The modeling approach consists of two main stochastic simulations steps. First of all we build successive topographies by stacking one after another DS simulations of erosion-deposit events over an initial topography. Each erosion-deposit event is conditioned by the previous topography state. Then the layers, corresponding to what remains of one event, are eventually gathered to constitute main layers. The last step consists in simulating with the DS algorithm heterogenous facies inside the main layers, previously defined.

1 Building successive topographies

1.1 Defining Training Images

Building successive topographies necessitates two kinds of simulations. First we shall be able to simulate an initial topography. This can be achieved with the DS algorithm, using a DEM as TI. At this stage data conditioning is interesting only if fields data are available.

Then we shall generate erosion-deposit events so that the average resulting topography increases. So we compute an erosion deposit event TI by substracting two DEMs of the same river at different time intervals so that the average difference of elevation is positive. Here as an event is related to the previous topography, the TI is composed of two variables :

1. *erosion-deposit event* - the difference of elevation between the two DEM,
2. *previous topography* - the topography values of the substracted DEM.

1.2 Description of the algorithm

To start with the method, we define I as the maximum number of timesteps. For each timestep $0 \leq i \leq I$ we denote L_i the remaining layer's thickness after all erosion-deposit events took place. The algorithm proceeds as follows (Fig. 1) :

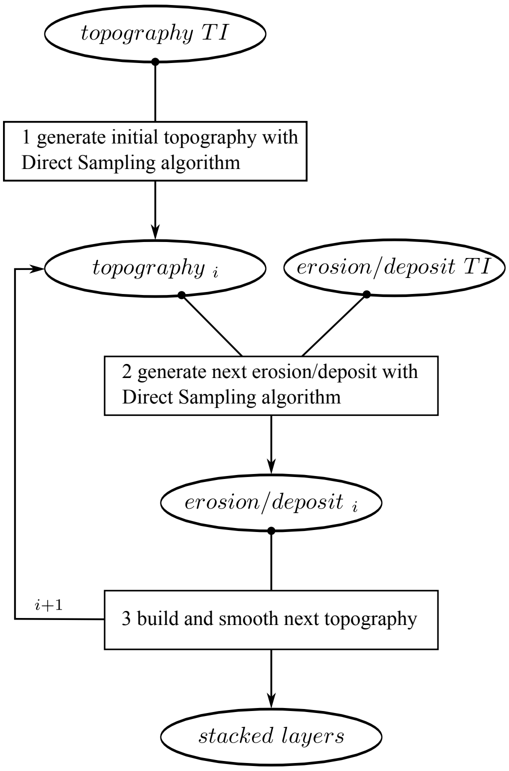

Fig. 1 Overview of the method to generate successive topographies

1. The first timestep is set to zero ($i = 0$). A first topography $\mathbf{z}_0^\circ$ is simulated with the DS algorithm to initialize the process before entering a loop. Then the initial topography is smoothed from $\mathbf{z}_0^\circ$ to $\mathbf{z}_0$. The smoothing operation is necessary to avoid artifacts and their cumulation through the successive simulations. The initialization layer L_0 is set with the first smoothed topography value $\mathbf{z}_0$

2. The i^{th} erosion-deposit event denoted $\delta\mathbf{z}_i$ is simulated using smoothed topography $\mathbf{z}_i$ as conditioning data.
3. We then compute the next timestep topography $\mathbf{z}^{\circ}_{i+1} = \mathbf{z}_i + \delta\mathbf{z}_i$ and the next layer's thickness $L_{i+1} = \delta\mathbf{z}_i^{+}$. The resulting topography is then smoothed so that it can be used as conditioning data ($\mathbf{z}_{i+1}$) for the next simulation. For all preceding timesteps j $(0 \le j \le i)$ the remaining layer L_j related to the j^{th} deposit is updated. i is incremented of 1. The algorithm loops to step 2 as long as the maximum number of timesteps I is not reached.

It is also possible to stop the algorithm when a satisfying thickness of deposits is obtained.

1.3 Example

The wide range of values for topographies or erosion-deposit events makes it difficult to simulate directly these continuous variables with the DS algorithm. Therefore we guide the simulation by discretizing the continuous variables through thresholds definition. We then generate a first simulation of the categorical variable, which is used as conditioning data in a second step to generate the continuous variable through a bivariate simulation.

Fig. 2 illustrates successive realizations of topography and erosion-deposit with the DS algorithm as described in section 1.2.

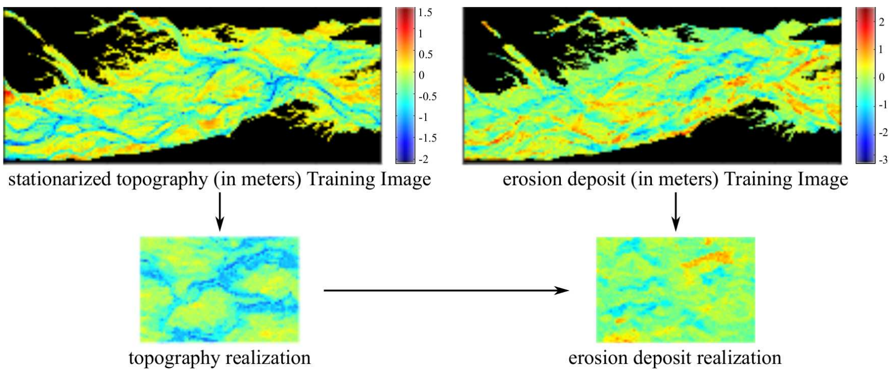

Fig. 2 Training Images (726 × 301 px) for DS algorithm and its realizations (300 × 200 px). Highest points in the topographies are represented in red whereas lowest points are in blue. Greatest deposits are colored in red while greatest erosions are colored in blue.

As we can see, the realizations of topography or erosion-deposit event obtained after guiding the simulation are satisfying : it respects the dominant patterns, channels and islands, present in the TI without copying exacltly some part of the TI.

2 Methodology for generating facies inside main depository layers

Once we obtained $I+1$ deposit layers L_i $(0 \leq i \leq I)$, it is possible to regroup some of these layers to build main layers. The gathering criteria depend on different available informations. We shall take into acount the aquifer structure to model if we dispose for instance of GPR data. We shall also consider the dynamic of the river wich is related to the amplitude of the erosion-deposit events. And we shall look carefully at the lengths scale of the Training Images used for erosion-deposit events simulations and for facies populating.

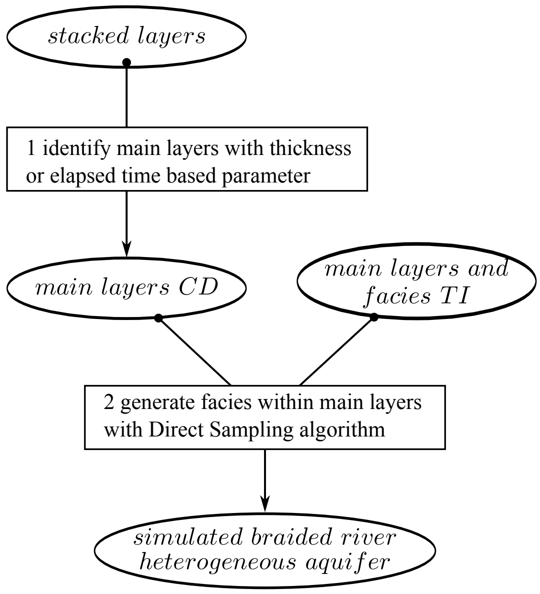

Fig. 3 Overview of the method to populate the main layers with different facies. CD : conditioning data. TI : training image.

Then the main layers are used as conditioning data to simulate facies within these main layers with the DS algorithm. At this step, we use a 3D bivariate TI. One variable represents the facies and the other the main layers. It results in obtaining a 3D model of an heterogenous aquifer in a braided river framework.

Conclusion

As far as we know there were no modeling approach combining braiding processes and heterogenous deposits. Up to date, most of process imitating numerical models focused on the braiding process in the framework of braided rivers systems [7, 9] and lengths scales were validated thanks to descriptive methods [2, 4, 8].

The novelty of our method relies in encapsulating the DS algorithm, a MPS technique within a process based algorithm. It helps to bring realism when process based methods fail or are too complicated or too costly to implement. In our case each erosion-deposit event that could be a process based realization is replaced by MPS pixel based simulations realized by the DS algorithm. It opens further modeling possibilities when classical tools issued from descriptive or process-based methods are limited by simulation realism or data conditioning.

Acknowledgments

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