ADVANCES IN QUANTIFICATION OF PROCESS-BASED MODELS FOR MEANDERING CHANNELIZED RESERVOIRS

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ABSTRACT

Process-based models allow generating realistic sedimentary bodies and arrangements in complex environments such as fluvial meandering systems. The model consists in (1) migration of the channel with deposition of sandy point bars according to hydraulic equations, (2) aggradation (building-up) of the system caused by overbank floods with construction of levees and deposition of shales vanishing further away in the floodplain, and (3) levee breaches resulting in new channel paths (avulsions). The efficiency of the model depends on the appropriate selection of processes and ruling parameters, and results in 3D blocks models for reservoirs. While the qualitative influence of each parameter is easier to understand, their quantitative contribution is difficult to assess. In this paper we develop an assessment of the principal volumes being deposited and propose a formula giving an order of magnitude of the sand proportion. For this we make a heuristic use of the Boolean model, taking as the individual object the set of points made by the meandering channel between two avulsions. An application to a real case study is included.

INTRODUCTION

Stochastic process-based models allow generating bodies and arrangements with a realism that may be difficult to obtain by the purely stochastic techniques proposed by geostatistics. This is the case of the reservoirs deposited by a meandering channel studied here. We use the comprehensive model developed initially by Lopez (2003), now called Flumy. This depends on a few key parameters, and includes tools that control the spatial distribution of the deposits and their conditioning to data.

Despite the limited number of parameters, the model is capable to reproduce various architectures. The influence of each parameter is generally clear. However, when modelling a reservoir, it is not easy to choose the parameters values, as it is difficult to assess the joint quantitative contribution of these parameters. Of course one can proceed by trials and errors, launching repeated simulations until he obtains a satisfying result. But it is better to have tools giving the order of magnitude of the parameters. In the following, after reminders of the model and its parameters, we present an approach to quantify the influence of parameters on deposited volumes, and to have in particular an order of magnitude for the resulting Net/Gross (sand proportion).

THE MODEL

The Elements of the Model

Migration of the Channel

The evolution of the channel in time and space is represented by equations developed by Ikeda et al. (1981), revisited by Sun et al. (1996). These are recognized as capturing the essential factors acting in the long term (Camporeale et al., 2005). Let w and h, supposed constant, be the width and mean depth of a channel cross-section. The channel flow equals Q = w H U, where U is the mean velocity. At steady state, this velocity is given by:

$$U = \sqrt{\frac{g\,H\,I}{C_f}} \tag{1}$$

where $C_f = 0.0036$ is the friction coefficient, $g = 9.81$ m/s² the gravity; and I the channel slope (typically 0.001). The migration of the channel at its outer bank is proportional to the velocity perturbation u at that point (difference between velocity and average velocity, typically a small fraction of this): $\zeta = |u|E$, where E is the erodibility coefficient. Finally this velocity perturbation is proportional to the channel width and obeys a differential equation which can be written as:

$$U\frac{\partial u}{\partial s} + 2\frac{U}{H}C_f\,u = \frac{w}{2}\left[-U^2\frac{\partial C}{\partial s} + C_f\,C\left(\frac{U^4}{gH^2} + A\frac{U^2}{H}\right)\right] \tag{2}$$

where C = C(s) is the curvature at curvilinear abscissa s, and A a scour factor taken here as 7. This equation describes the migration of the channel in time, and is solved by time iterations, 1 iteration representing grossly 1 year in temperate regions (as currently agreed, a normal erodibility value is taken as giving a migration of 0.63 m per iteration for a velocity perturbation of 1 m/s). The meandering wavelength is found to be practically proportional to the mean depth (800 H). While migrating, the channel erodes the outer bank and deposits sandy point bars on the inner bank, which have good reservoir properties. Migration tends to increase the meanders, and so the lateral extension of the channel, but this phenomenon is stabilized by cutoffs of the channel, then creating an abandoned channel filled by mud plug (Figure 1).

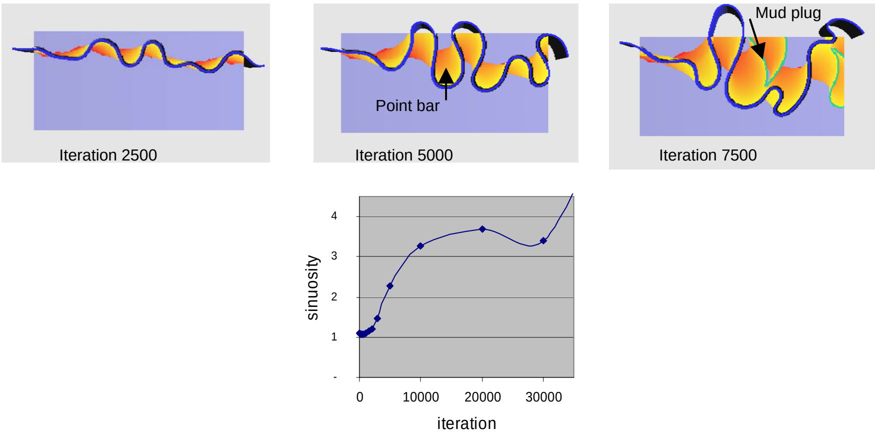

Figure 1*:* Channel meandering in time, depositing point bars (red to yellow) and mud plug (green) in abandoned loops (top). The sinuosity begins small, then increases and fluctuates (bottom).

Aggradation

While migration corresponds to a lateral subhorizontal movement of the channel, the aggradation of the system corresponds to a vertical upward movement. At every overbank flood (occurring periodically or randomly with a given frequency f_{ob}), there is deposition of a sandy channel lag on the channel bottom and deposition of fine overbank flood sediments such as shale on the levees and further away on the floodplain. The intensity of the overbank flood i_{ob} gives the thickness of the channel lag and the increase of the elevation of the levees. The thickness and granulometry of overbank sediments decrease away from the channel as a negative exponential with specified range λ. Between two overbank floods, there may be deposition of peat in the lowlands, with a thickness proportional to the time interval between the overbank floods, rapidly compacted afterwards.

Avulsions

Due to the aggradation, the channel tends to dominate its floodplain. But levee breaches may occur randomly, preferentially where the velocity perturbation is larger. This leads to crevasse splays (small volumes), then possibly to a new path for the channel (avulsion), chosen preferentially when this increases the slope downwards. As levee breaches may occur upstream of the modelled domain, so-called regional avulsions, correspond to new entry points in the domain.

On Domain and Conditioning

The 2D domain to be simulated is rectangular, dipping slightly in the W-E x-direction conventionally taken as the direction of flow. The above processes occur within this domain, but also outside of it. The processing outside the domain cannot be ignored because it influences what happens within the domain. Developments have been made on this, in order to eliminate borders artefacts, and in particular to be able to simulate a stationary system (Rivoirard et al., 2007). In brief the processes outside the domain are necessarily simplified, but are present within a domain extended by lateral margins (where in particular regional avulsions can be generated), and by upstream and downstream margins (where in particular the behaviour of the migrating channel is initiated). The underlying hypothesis of the system is this of one channel being present within the laterally extended domain at any time iteration of the model (hence the model does not take into account avulsions that would send the channel outside of this). Note that stationarity in our case is less a necessity of the model as usually in geostatistics, than a way to be able to control a possible stationarity or non-stationarity. Non-stationarity, as indicated by an uneven distribution of sand within the domain as inferred from seismic, for instance, can be taken into account through a map of erodibility, an "Emap" (Lopez, 2003, Cojan et al., 2005). A methodology has also been developed to generate simulations approximately conditional on well data. Typically migration or avulsion of the channel is favoured towards sand datapoints to be honoured, away from shale datapoints (Lopez, 2003; Rivoirard et al., 2007).

Key parameters and their qualitative influence

The model depends essentially on a limited number of key parameters:

- channel width w, mean height H, and slope I;
- erodibility E;
- frequency f_{ob} and intensity i_{ob} of overbank floods;
- thickness exponential decrease of overbank sediments λ;
- area of lowlands to be covered by peat, as a percentage of domain area;
- frequency f_{av} of avulsions.

Given the above description of the model, the qualitative influence of these can be summarized as follows. For simplicity we will consider essentially sandy bodies (including associated mud plugs) and overbank sediments (including levees), and neglect crevasse splays and peat. The larger the height H, the width w, the erodibility and the slope I, the higher the velocity and the migration. As channel migrates, sand bodies develop laterally, increasing or maintaining meandering and sinuosity. Aggradation (i.e. its parameters: frequency f_{ob} and intensity i_{ob} of overbank floods, thickness decrease λ) makes sand bodies develop vertically, but reduces sand proportion while increasing proportion of overbank sediments. Finally avulsions frequency is responsible for more numerous but less developed meander loops, spaghetti like. We will now present an approach to quantify the influence of parameters on the deposited volumes.

QUANTIFICATION OF THE INFLUENCE OF THE PARAMETERS

Assessment of Individual Volumes

Sinuosity (S) is defined as the ratio of the channel length by the distance between its extremities (which can be approximated by the x-distance). Generating a nearly straight channel on a slightly dipping plane gives a sinuosity starting small (~1.1), then increasing and fluctuating grossly around 3.5 (Figure 1). In the model the sinuosity increases with $w\ U\ E\ \Delta t$ (Δt = time interval), this being around 0.014 to get a sinuosity of 1.5, conventionally taken as the threshold between a small and a large sinuosity.

To quantify the model, it is convenient to consider generic sections orthogonal to the channel, and then x-sections orthogonal to the valley. For the channel itself, (the measure of) its cross-section is simply the product of its width by the mean depth w*H. Now the average measure of the 2D x-section of the channel is simply equal to S*w*H, per definition of the sinuosity. Note that this average cross-section includes the case of an x-section with several connex components (Figure 2).

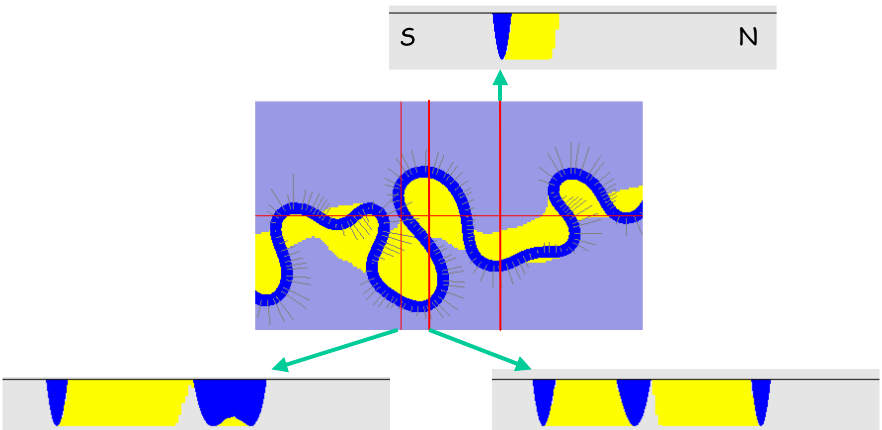

Figure 2: Different x-sections of channel.

In the model the aggradation is obtained by the deposition of channel lags and of overbank flood deposits (possibly replaced later by point bars with no change on aggradation). The channel lag deposited during an overbank flood in a cross-section of the channel is simply equal to $w\ i_{ob}$, so that the 2D-volume of channel lag deposited during Δt in an x-cross-section is equal to:

$$CL(\Delta t) = S\ w\ i_{ob}\ f_{ob}\ \Delta t \qquad (3)$$

Here the sinuosity is the average sinuosity during Δt, not the instantaneous sinuosity. Taken the other way round, recording CL as a function of time is a way to measure the average sinuosity.

The overbank flood deposits are more difficult to handle. Within a section orthogonal to the channel, the maximal 2D-volume deposited during an overbank flood corresponds to the volume under the negative exponentials on both sides of the channel, that is $2\lambda\, i_{ob}$. When looking at the maximal 2D-volume deposited on an average x-cross-section during a time interval Δt, this has to be multiplied by S * f_{ob} *Δt. However the effective volume deposited is lower than this, because the effect of the sinuosity vanishes if the range parameter is large and meanders small, and above all because there is no overbank sediments deposited away from the channel where the current topography increases. In the following, we have adopted the formula:

$$OB(\Delta t) = S\, k_{ob}\ \lambda\ i_{ob}\ f_{ob}\, \Delta t \tag{4}$$

with the average sinuosity and a coefficient k_{ob} < 2, and further estimated as 1.2. Finally the average 2D-volume of aggradation deposited in an x-section can be written as:

$$Aggrad(\Delta t) = OB(\Delta t) + CL(\Delta t) = S\,(k_{ob}\,\lambda + w)\ i_{ob}\ f_{ob}\,\Delta t \tag{5}$$

The aggradation rate can be deduced:

$$Aggradation\, rate\,(m\,/\,iteration) = \frac{S\,(k_{ob}\,\lambda + w)\ i_{ob}\ f_{ob}}{domain\, width} \tag{6}$$

Finally point bar is the most difficult to estimate. The point bar deposited by a migrating channel in a channel cross-section during a small Δt is $H\,\zeta\,\Delta t$, with migration rate $\zeta = |\,u\,|\,E$. The velocity perturbation |u|, proportional to w, is also a fraction of the average velocity U. Then the 2D-volume of point bars deposited on average in an x-section during Δt can be written as:

$$PB(\Delta t) = S\, H\, w\, k_{mig}\ U\, E\, \Delta t \tag{7}$$

using the average sinuosity. In this formula, the coefficient k_{mig} (in m^{-1}) is expected to depend on Δt, in particular decreasing when the meandering is well developed and new deposited PB replaces older PB). It was possible to deduce k_{mig} by dividing PB and CL for a channel migrating and aggrading, showing a slight decrease with time around 0.004. In the following k_{mig} has been taken as constant, equal to 0.004. It is assumed not to be affected by aggradation.

The Meandering Channel Object

By the important concept of meandering channel object, we mean the set of points that has been occupied by the channel at some time within an interval Δt. Its average 2D-volume in an x-section can be deduced from the above formulas:

$$K_{\Delta t} = (S\,w H) + PB + CL = S\,w\,(H + H\,k_{mig}\,UE\Delta t + i_{ob}\,f_{ob}\,\Delta t) \tag{8}$$

It follows that the proportion of sand, corresponding to one channel migrating and aggrading can be written as:

$$sand(\Delta t) = \frac{K_{\Delta t}}{aggrad\,(\Delta t)} \xrightarrow[\Delta t \uparrow]{} \left(\frac{1}{1 + \frac{k_{ob}\,\lambda}{w}} \right) \left(1 + \frac{H\,k_{mig}\,U\,E}{i_{ob}\,f_{ob}} \right) \tag{9}$$

However the use of such a meandering channel object will be more interesting when adding avulsions, as just now.

The Boolean Formula for Sand

It is very difficult to forecast the sand proportion resulting from our process-based model. We know the qualitative influence of the parameters, but are rarely able to predict their joint influence. For this, we will resort to another model, the Boolean model, for the extraordinary tractability of its formula. The Boolean model consists in the union of independent objects, located at random points in space. In more details, objects are located at Poisson points with density θ. Objects are possibly random, independent on their location, and tossed according to the same distribution. Then, if K is the average volume of an object, the expected proportion of space occupied by the objects is equal to: 1 – exp(θ K) (Matheron, 1967).

The originality of the approach proposed here is to represent the meandering channel model by a 2D Boolean model, where the 2D space is an x-section and where an object is our meandering channel object between two successive avulsions. From (8), the 2D-volume of such an object is:

$$K_{av} = (SwH) + PB + CL = Sw\left(H + H\,\frac{k_{mig}\,UE}{f_{av}} + \frac{i_{ob}\,f_{ob}}{f_{av}} \right) \tag{10}$$

while the 2D density is the average number of avulsions reported to aggradation:

$$\theta = \frac{f_{av}}{S\,(k_{ob}\,\lambda + w)\,i_{ob}\,f_{ob}} \tag{11}$$

This gives the expected proportion of sand:

$$sand = 1 - \exp\left[-\left(\frac{1}{1 + \frac{k_{ob}\,\lambda}{w}} \right) \left(1 + \frac{H}{i_{ob}\, f_{ob}} \left(f_{av} + k_{mig}\, UE \right) \right) \right] \tag{12}$$

to be used as an order of magnitude for sand in our process-based model. Further tuning from simulation of the process-based model has lead to adopting values k_{ob} = 1.2 and k_{mig} = 0.004 for the additional coefficients.

The Boolean formula has also been used for a sensitivity analysis of the different parameters on sand (Figure 3). This shows, under the hypotheses made, that sand is more sensitive to channel width and depth, overbank intensity, period and thickness parameter, and to erodibility. And it is poorly sensitive to the slope and the frequency of avulsions.

Case Study

The meandering channelized reservoir model has been applied to two successive units of the formation of Loranca, south-east of Madrid (Diaz-Molina et al., 1995). Most important field observations for our purpose are the followings. Measures of the depth of channels were made, leading to choosing a mean channel depth of 2.5 m. According to the analysis of actual systems, this corresponds to a channel width around 80 m. The average velocity of the flow can be deduced (2 m/s). Point bar outcrops present up to 2000 successive laminations with thickness 5 mm, each lamination representing a migration iteration (6 mm horizontally). According to the formula, the migration would be of 0.40 m per iteration using the normal erodibility value. In order to have a migration of 0.006 m, we need to choose an erodibility equal to 0.015 times the normal one. While laminations could be clearly observed on a 12 m outcrop, the extension of point bars can be expected to be a few hundreds meters, taken at maximum at 400 m by choosing a frequency of avulsions equal to 1/60000. The overbank flood intensity could be assessed to 0.5 m, an upper bound for observed levees. Such a value is typical of sheet floods with little decrease in thickness away from the channel. Consequently a large thickness decrease parameter of 3000 m was chosen. Finally the overbank frequency was deduced from the sand proportion and previous parameters using the Boolean formula. The sand proportion was calculated from different field sections. It was found equal to 0.36 for the lower unit, presenting amalgamated channels, and 0.18 for the upper unit, with isolated channels. This led to an overbank frequency of 1/40000 for the lower unit, and 1/16700 for the upper one.

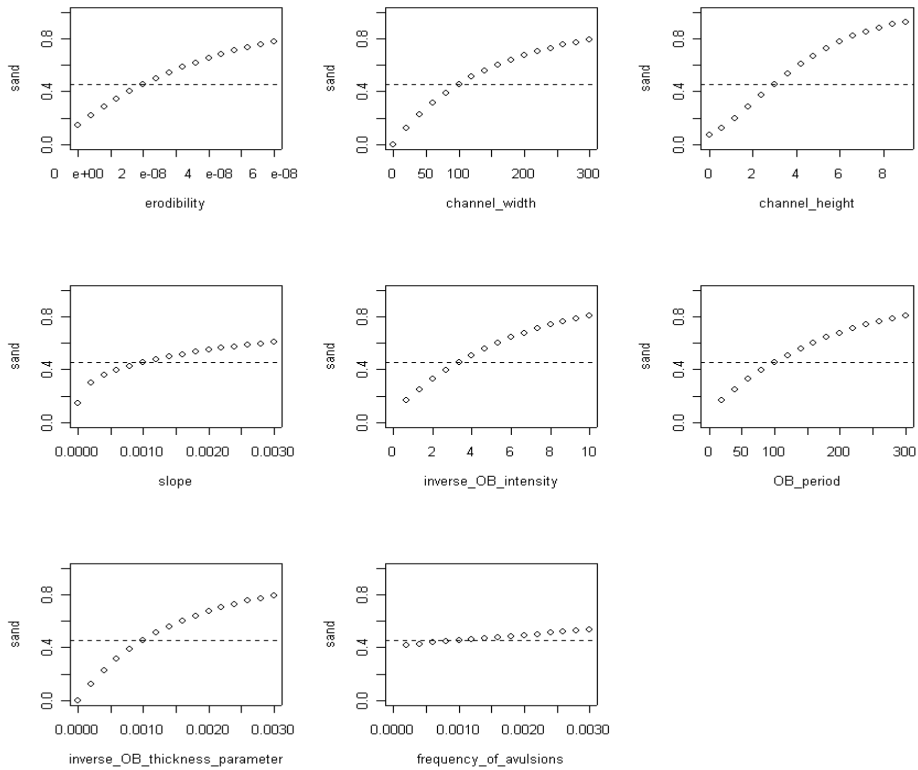

Figure 3*:* Sensitivity analysis of sand by varying each parameter while maintaining the others fixed in the Boolean formula (normal erodibility, channel width 100 m, mean depth 3 m, slope 0.001, overbank flood with intensity 0.3 m, frequency 0.01, and thickness parameter 1000 m, avulsions frequency 0.001).

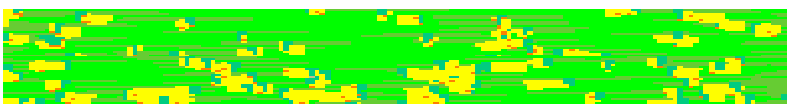

Figure 4: Cross-valley section of a simulation in Loranca meandering channelized system (6 km wide x 40 m high). Note the lower unit with amalgamated channels, and the upper one with isolated channels (yellow: point bar sand; orange: channel lag sand; blue: mud plugs; green: overbank shales; dark green: levees).

Simulations were performed with the determined parameters. Results clearly show the difference between the amalgamated channel in the lower unit, and more isolated ones in the upper unit (Figure 4). They give sand proportions equal to 37% and 20% for the two units. Given the uncertainty on the parameters, such an agreement is essentially due to chance. Various other data-free simulation tests (not presented here) have shown that, while not designed to be precise, the sand formula was helpful to deliver orders of magnitudes, taking into account jointly the key parameters. Note that the sand formula can be used, either to predict the order of magnitude of the sand knowing the model parameters, or to choose parameter values knowing the others and the desired sand proportion.

CONCLUSION

To quantify the influence of the model parameters on the resulting simulations, first we have made a raw assessment of the principal volumes that are being deposited. In doing this, we have made drastic simplifications in order to obtain orders of magnitude, in the spirit of the back-of-the-envelope calculations favoured by the physicist Fermi.

Then we have assimilated our process-based model to a Boolean model. This has enabled us to use the Boolean formula, as a plausible formula for the order of magnitude of the sand proportion knowing the parameter values. In short we have made a heuristic use of the Boolean formula. (Note that this situation is not rare in geostatistics: the (multi-)gaussian model of Random Functions is essentially used for its extraordinary simple properties and the consistency of its results: but beyond univariate and possibly bivariate distributions, who checks the normality of higher multivariate distributions that fund the model?).

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