Use of Cellular Automata Flow Model in the Hybrid Geostatistical Models: A Proposal

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Abstract
The idea of hybrid modeling is to decompose a single modeling problem into a set of smaller problems and model each of them with proper methods respectively, honoring the advantages of a variety earth modeling methods. The objective is to obtain a balance of geological reality, the representation of the uncertainty with a fixed set of initial parameters and the capability of being conditioned to the hard data as well. Many workers have used geomorphologic/geomorphologic laws in the hybrid modeling of submarine channel-lobe system. Honoring the flow direction calculation algorithm and the updated topographic map, better geological reality is obtained and the geomorphologic laws are proved to be capable of improving the model’s geological reality. For effectively utilizing more geological laws, an algorithm based on Cellular Automata (CA) is proposed to improve the structure and the erosion of the model. Furthermore, an inversed flow routine algorithm calculating the upslope areas is proposed to condition the model to hard data.

1. Introduction
The idea of hybrid modeling is to decompose a single modeling problem into a set of smaller problems and model each of them with proper methods respectively, honoring the advantages of a variety earth modeling methods. The objective is to obtain a balance of geological reality, the representation of the uncertainty with a fixed set of initial parameters and the capability of being conditioned to the hard data as well. Some previous works including Pyrcz et. al. 2003, 2005, Micheal et al., 2008 and Leiva et. al. 2009. These works are attempting to model a submarine channel-lobe system, in which process-based models are used to provide geometric parameters of geobodies, the object-based modeling is used to construct training images (TI) from the geometric parameters and finally, Multi-Point Statistics (MPS) are used to condition the model to hard data. Micheal’s work gives a first-step schema of hybrid
modeling, and Leiva introduces the use of geomorphologic laws to enhance the geological reality. The improved method better models the geometry, the erosion and deposition. However, there are still improvements to be made. The major challenge is that the geomorphologic laws used are not sufficiently specific, which makes the modeled geological features not as satisfying as we expected. For example, the degree of erosion is determined by the flow direction, the hillslope gradients and the hillslope curvature in a static manner in Leiva’s algorithm. These parameters do affect the erosion and deposition process, but they work dynamically in conjunction with the turbidity flow. The dynamic erosion and deposition effect should be modeled dynamically. The proposed algorithm attempts to dynamically use geological/geomorphologic rules in a Cellular Automata schema, which aims to both improve the geological reality of the hybrid model and avoiding the intensive computational cost of process-based equations. Another proposed algorithm is to inverse the flow direction calculation algorithm to condition the model to local data.

2. Literature Review

2.1. Hybrid Models

2.1.1. Former Hybrid Models Revisited

Micheal et al.’s (2008) and Leiva’s (2009) hybrid algorithms are described in details by flowcharts (Figure 1A and B) as follows. The two algorithms follow similar ideas of using different modeling methods. The process-based models (PBM) are used as a database, from the CDFs of the parameters of the geometries of the geobodies are inferred; the object-based modeling (OBM) is used to construct the TIs for the sake of honoring its efficiency; MPS is used to condition the simulation to the hard data; both formulations involve rule-based methods in modeling. Micheal used geological laws to generate depositional and erosional maps as TIs for MPS simulation and Leiva used more specific laws to determine the gravity flow direction and the drainage basin area. Moreover, Leiva utilized the geological law that the shape of the channel-lobes is determined by the topography by updating the topography map after every new geobody is simulated.
2.1.2. Discussion

Comparing the two algorithms, it is the more specific geomorphologic rules adopted in Leiva’s model that enhances the geological reality. The reason is that the geological reality of Micheal and Leiva’s algorithms are provided by the distributions of the parameters characterizing the geometries of geobodies in the PBM. However,
the erosion and deposition parameters are hard to infer (Micheal et al., 2008). Therefore, the other way to better geological reality is by adopting rule-based modeling methods, which approximates reality instead of solving computationally intensive physical equations. In fact, we may consider the rules as human’s intuitive understandings of the physical equations. Using the water flow direction as an example, we can say that the water always flows along the locally steepest direction instead of calculating a complex equation system involving gravity and other hydraulic variables. Because the rules are just intuitive approximations to the physical equations, they are limited to be considered correct in small spatial and temporal scales. For example, although we can say that water always flows down, the statement that a stream starts in the mountain will surely flow down to the ocean is not correct, because of regional special environment such as an alpine lake that may contained the water. Thus, if we are going to use some more specific geological/geomorphologic laws, we have to find a technique which is capable of using the rules at the local scale, in such a way that the resulting global structures of our models may be considered acceptable.

2.2. Cellular Automata

2.2.1. Cellular Automata in Landscape Modeling

Without involving into obscure mathematical definition, I would rather use a descriptive definition of CA from Wolfram (1984). In his definition, a CA model includes five key factors

- A CA consists of a discrete lattice of cells;
- The CA involves in discrete time steps;
- Each cell takes on a finite set of possible states
- The state of each cell evolves according to the same deterministic laws;
- The laws for cell evolution depend only on interactions with neighboring cells;

He further stated that

“even though the elementary components of a system may follow simple laws, the behavior of the large collection of components which comprise the whole system may be complex”

Wolfram, 1984

Due to the inherent features of CA, it has been widely used to model landscape evolution since 1970s. The first generation of CA landform models are limited in very small grids due to the limit of computation facilities, but with the development of the
computer hardware, the scale of CA models keeps increasing. In the last decades, several CA-based fluvial models have been constructed and proved effective. Coulthard’s (2002) model CAESER (Cellular Automata Evolutionary Slope And River) successfully simulated the evolution of a river section from the scale of seconds to the scale of 10 thousand years. Coulthard uses a square grid. In the lattice, the stream flows in a valley where the dark dots represent precipitation added to each grid. At each time point, the grid is scanned four times from four directions, moving precipitations of each grid to the neighboring grids with lower elevation, with erosion and deposition happen according to some hydraulic equations. CA has been applied to simulate submarine density currents as well (Salles, 2007, 2008.). In Salles’ model, each cell of the lattice is considered as a column containing water and mass and the transport occurs between neighboring cells, from the one with more water and mass mixture to the one with less. The erosion and deposition process follows simplified hydraulic laws. Both Coulthard’s and Salles models to some extent effectively modeled the fluvial processes, and their ideas would be utilized in the proposed CA models. In the proposed algorithm, a square grid will be utilized combining the concept of column container of Salles’ model.

2.2.2. Discussion

As demonstrated in the previous section, CA models are actually quasi-process-based models, which model the phenomena in the perspective of reproducing the processes forming them. However, some intuitive rules could be utilized in CA instead of the physical equations, so that the process-based global patterns could be approximated without intensive computational costs.

2.3. Submarine Channel-Lobe System Growth Model

2.3.1. Conceptual Channel-Lobe Model

To begin with the study, we have to define a model more or less with respect to the process. Recent geological research have summarized information on the morphology of typical submarine channel-fan systems

Ven Kolla (2007) reviewed the recent studies on the Amazon, Zaire, Indus and Bengal Fans. It is found that the growth of submarine channel system is a complicated process co-determined by base topography, channel sinuosity increase, channel lengthening, channel thalweg and levee aggradations, climate, tectonic activity, peak volume flows, sediment grain sizes and bank erosion, and the presence of previous channels. The growth of the channel network is caused by avulsion along parent channels. The point that avulsion happens is called avulsion point. The avulsion points probably appear around the region with high instability. The
instability condition is the ratio of the gradient of the bank slope that avulsion possibly happens to the gradient of currently active channel (Figure 2), or

\[
\frac{Sa}{Se} = \frac{\text{Gradient of the bank slope that avulsion possibly happens}}{\text{Gradient of currently active channel}}.
\]

![Figure 2: Demonstration of bank instability. Modified from http://content.swgfl.org.uk/rivers/images/flashimages/oxbow.gif.](http://content.swgfl.org.uk/rivers/images/flashimages/oxbow.gif)

While this ratio increases, the instability increases. But simply high instability of a segment of the channel does not ensure the occurrence of avulsion. Some additional random factors such as peak volume flow and tectonic uplift will trigger the avulsion. Kolla also stated that the submarine flows, as well as the subaerial flows, always trying to find the shortest channel to the regional basin and deposit their load to generate the lobe body..

Covault (2009) reviewed the growth pattern of submarine fans in confined basins, and compared it with the submarine fan growth in the unconfined setting (Figure 2). The different fan growth models demonstrated that the pattern of the lobe is determined by both the topography and the flow volume. With repeated filling, the lobe will extend basin ward. If it is in a confined setting, a new lobe will be generated after the basin of the old lobe is filled up; while the old lobe will simple be covered by a new lobe in the unconfined setting.
2.3.2. Discussion

According to the above description, several rules are inferred:

- The submarine density current always trying to find the shortest way to the regional lowest point, which means the channel path is deterministic;
- The avulsion points appears near the channel segments with high instability, but the appearance of avulsion is random;
- The formation of a lobe starts when the current reaches the lowest point of it can reach.

These three intuitive geological rules are important in the construction of the model.

3. Methodology

There are two key improvements of this proposed method to Salles et. al. (2008). First, the avulsion in this proposal is considered as stochastic; second, a geomorphological rule-based conditioning simulation algorithm is proposed.

3.1. Data Overview

The Shell Lobe Model is a geometric property submarine channel-lobe model provided by Shell Oil Exploration Corp. This model will be used to infer the distribution of the geometric parameters of geobodies. The model is located in a 1380 m × 1380 m × 15m region of a channel-lobe system (Figure 4 A, B, and C).
Figure 4: (A) Shell Lobe Model; (B) East-West Cross Section; (C) North-South Cross Section.

Major events are inferred from East to the West. The deposition feeder is located in the range [800, 1200] on the y-axis. Erosion and deposition events cause complex
structures of the turbidite system. Four facies appears in this model: distributary channel sand, inner levee sand, lobe axis sand, and lobe margin sand (Figure 5). The distributions of the parameters will be inferred from this model.

Figure 5: Facies and Porosity.

3.2. Proposed Workflow

3.2.1. Parameter Characterization

Due to the inherent difference between the proposed method and the previous method, the parameters to be inferred are significantly different (Table 1).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Annotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Topography</td>
<td>To Control the channel direction and lobe geometry and location</td>
</tr>
<tr>
<td>Lobe volumes</td>
<td>To the Length of Each Deposition Events</td>
</tr>
<tr>
<td>Avulsion Point Width</td>
<td>To Control the Beginning Width of an Avulsion</td>
</tr>
<tr>
<td>Distance from Avulsion Point to Closest Max{Sa/Se} point</td>
<td>To Randomly Draw Avulsion Point Surrounding a Most Instable Point</td>
</tr>
<tr>
<td>Maximum Deposition Depth</td>
<td>To Stop Simulation</td>
</tr>
<tr>
<td>-------------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>Number of avulsions/Number of Depositional Event</td>
<td>Useful in Creating the Avulsion Probability Map</td>
</tr>
</tbody>
</table>

Table 1: Parameters for Characterization

3.2.2. Automaton Cube and State Space

In the lattice of the proposed CA model, each cell is considered as a cubic container, in which a fluid layer, a fine grain layer and a coarse grain layer are included (Figure 6).

![Automaton cubic cell model](image)

Figure 6: Automaton cubic cell model.

For each cell, we take several features, from both the fluid and the sediments.

Fluid thickness, \( T_w \)

Fluid velocity, \( V \)

Outflow from the cell, \( O \)

Fine grain thickness, \( T_f \)

Coarse grain thickness, \( T_c \)
Fine grain concentration, \( C_f \)

Coarse grain concentration, \( C_c \)

Cell elevation, \( E \)

A set of specific values to these features determines the state of cell \( i \) at time step \( j \):

\[
S_{ij} = \{(T_w)_{ij}, (V)_{ij}, (O)_{ij}, (T_f)_{ij}, (T_c)_{ij}, (C_f)_{ij}, (C_c)_{ij}\};
\]

All the possible values of \( S \) determines the state space of the CA model. The features of cell \( i \) at the next time step \( j+1 \) are determined by values of its values at time \( j \).

A set of regional rules are defined. Such as

Outflow rules: sediment and fluid transport between neighboring cells;

Fluid entrainment rules: the erosivity of fluid in a cell cube;

Erosion and deposition rules: bank-fluid and bed-fluid transport;

Thickness updating: updating the fluid/sediment thickness considering the inflow from neighbors;

The rules are defined functions on the features, for example, the outflow of cell \( i \) at time \( j \) is a function of current fluid velocity, fluid thickness, fine grain concentration, coarse grain concentration, and the cell elevation

\[
O_{i,j} = f((T_w)_{ij}, (V)_{ij}, (C_f)_{ij}, (C_c)_{ij}, (E)_{ij});
\]

Globally, the CA lattice is scanned four times in a single time step (Figure 7).
Black cells are with water, the scan is performed from four directions sequentially. In the scanning, water with higher elevation is pushed to neighbor cells with lower elevation.

### 3.2.3. Unconditional Simulation

In the case of unconditional simulation, the algorithm is relatively simple. First, the distributions of the parameters will be inferred from the existing model; Second, a P-field map will be generated based on the topology and some rules for the location of the point, and the location of the deposition feeder point is drawn from the P-field map; then the algorithm for flow direction determination will be performed to find the channel; after this, a lobe volume and channel width at the avulsion point is drawn from the cdfs; next, the CA model performs the current event along the predefined channel with the predefined rules and values drawn from the pdfs. After the volume is used up, the current depositional event is considered over. Then the topology map is updated with the latest simulated channel-lobe. The maximum deposition depth is checked for the new topology, if the maximum deposition is reached, step the simulation; or the instability along the channel is calculated and the avulsion point is randomly drawn, when the avulsion point is drawn out, repeat the algorithm from the point of flow direction calculation. The algorithm is demonstrated in the following flowchart (Figure 7).
3.2.4. Proposed Conditional Simulation (Inversed Upslope Area Searching Algorithm)

Submarine turbidity currents are gravity-driven currents, which may be considered analogous to subaerial fluvial systems. According to the algorithm in Torboton 1997, the flow direction always follows the steepest downslope direction. Conversely, the flow through a certain point is always from neighbors with higher elevations. The proposed conditioning algorithm starts from the conditioning data based on this rule. Figure 8 demonstrates the algorithm in detail. The algorithm will include two parts,
upslope area search (Figure 9 A to D) and stream simulation (Figure 9 E to H).

For a well located at cell A, a given searching depth d, upslope area searching is described as follows:

1. Start searching upslope area U from A;
2. When the distance from the edge of U to A is d, or U converge with another upslope area, stop;
3. Randomly draw a point A1 from U;
4. Replace A with A1, jump to 1;
5. If the upslope areas are not converged, reject the result and jump to 1;

Upslope searching moves upward in terms of elevation and will converge to the highest area H of the initial topography. Stream simulation starts from H and performs CA stream model within one upslope area at one time. The simulation will connect all drawn points and the hard data location, and stops when the sediment facies matches the well data.
Figure 9: Inversed Flow Appearance Calculation; (A) Two wells (diamonds); (B) Search the upslope areas separately for a given searching depth; (C) Randomly draw upstream points (stars) from the upslope areas; (D) Search the upslope areas for the new drawn points; repeat searching until convergence; (E) Draw the sediment source in the converged area; (F) Perform CA flow model from the highest upslope area; (G) Perform CA flow model from the upslope area adjacent to the simulated one; (H) Perform CA flow model from the upslope area adjacent to the latest simulated one;

4. Benefits of Study

The proposed method is to combine CA technique in the hybrid geostatistical modeling, taking advantage of geomorphological rules and latest geological studies
on the deep water turbidite system. There are two key improvements. First, the
proposed model considers both the certainty in channel routing and the uncertainty in
avulsion, such that stochastic realizations can be generated with a fixed set of
parameters. Second, an inversed-rule-based conditioning algorithm is proposed. The
method promises the appearance of channels on well data.

5. Acknowledgements

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