SCALING ISSUES IN SEDIMENTARY PROCESS MODELS

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Summary

In hydrocarbon reservoir description, the successful inference of bulk properties from point data has opened the door to practical applications of subsurface flow simulation. This review contends that in sedimentary process modeling, the successful inference of the behavior of large sedimentary systems from an understanding of local phenomena is the key to achieve wider practical applications of modeling.

Most geologic processes operate differently at various spatial and time scales. In order to use a model at a scale for which it was not originally designed, one must change the relative importance of terms in the governing equations to reflect their relative importance at the new scale. This procedure is illustrated by examples of upscaling and downscaling. Upscaling concerns sedimentation modelers because it remains difficult to use local principles of flow and sedimentation over periods of geologic time. Yet some examples show that models may actually become simpler (but not less rigorous) after upscaling.

A few geologic processes operate similarly over a wide range of scales. They result in truly fractal distributions of spatial properties. No change in the simulation model of such processes is necessary to make it operate successfully across many scales, but it remains the modeler's responsibility to validate the assumption of scale invariance.

Examples of published and proposed models as well as geologic data (in particular borehole images) support the conclusion that the study of scaling behavior leads to better theoretical foundations for sedimentation models while facilitating their practical application by revealing the model's properties that are most relevant to the problem's scale.

Introduction

Sedimentary process modeling is the simulation, by computer or in a laboratory, of the physical phenomena that erode, transport, and deposit sediments in natural environments. The purpose of modeling is to understand the nature of the simulated processes and to predict the configuration of actual geologic features between and beyond field data.

Modeling is necessarily a simplification, as it is impossible to model all processes taking place in a natural system. When defining a model, the issue of scale is critical. Only the processes that are relevant at the scale of interest should be modeled in detail. Processes that occur at space and time scales smaller than the resolution of the model can only be approximated in their bulk behavior. Processes that are much larger can be assumed to be fixed or can be represented as varying input or varying boundary conditions.

Geologic processes occur at many different scales, form continent wide to submicroscopic. They do not, however, produce similar shapes at all scales. Figure 1 shows the trace of the Gulf Coast of Texas at four different scales. At each scale, entirely different processes are in action. Models that work well at one scale may be totally inadequate at another. Yet it is often desirable to "stretch" the scale of a model upward or downward, for the following possible reasons:

1. Computer resources necessary may become prohibitive.
2. Model input and boundary conditions that dominate the system become different at different scales. For example, when simulating a river delta, the sediment and flow regime may be the most important controlling boundary conditions. When simulating over a few million years, however, sea

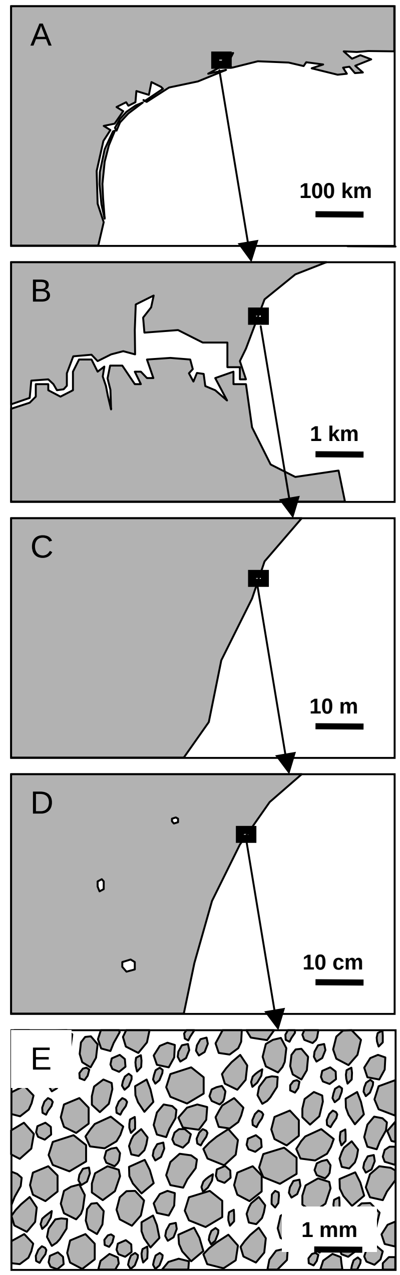

Figure 1: Portion of the coast of the Gulf of Mexico, successively enlarged by factors of 100. Each scale is dominated by different processes: (A) shelf and deltaic processes, (B) fluvial transport, (C) wave action, (D) bioturbation, (E) grain interactions.

level variations that may flood the entire system become dominant.

Spatial and time scaling

To illustrate the particular problems of model scaling, let us consider a simple "random-walk" alluvial-fan model. The model assumes that successive channels are generated by random walks. Every channel starts at the same point up slope. The channel consists of a number of segments. Each segment diverts sideways (left ot right of the downslope direction) in a fashion determined by drawing from a statistical distribution. For example, in a simple model, the direction can be: downslope, left, or right, each with probability 1/3. The channel cuts into preexisting deposits, but fills the cut with sediment with a volume exceeding the cut by a fixed fraction f of the channel area cross section A, so each channel aggrades, in cross section, by a surface equal to Af. The value of f, A, and the shape of the section depend on assumed paleoenvironmental conditions. A new channel is generated every year.

This model, however simplistic, may have practical applications in studying reservoir connectivity, as for example, in the sequence shown in the resistivity borehole images displayed in Figure 2. Borehole images are particularly useful for studies of scale because they provide detailed dip information from which depositional environments can be inferred (Bigelow, 1987), and up to 4 orders of magnitude of geologic detail.

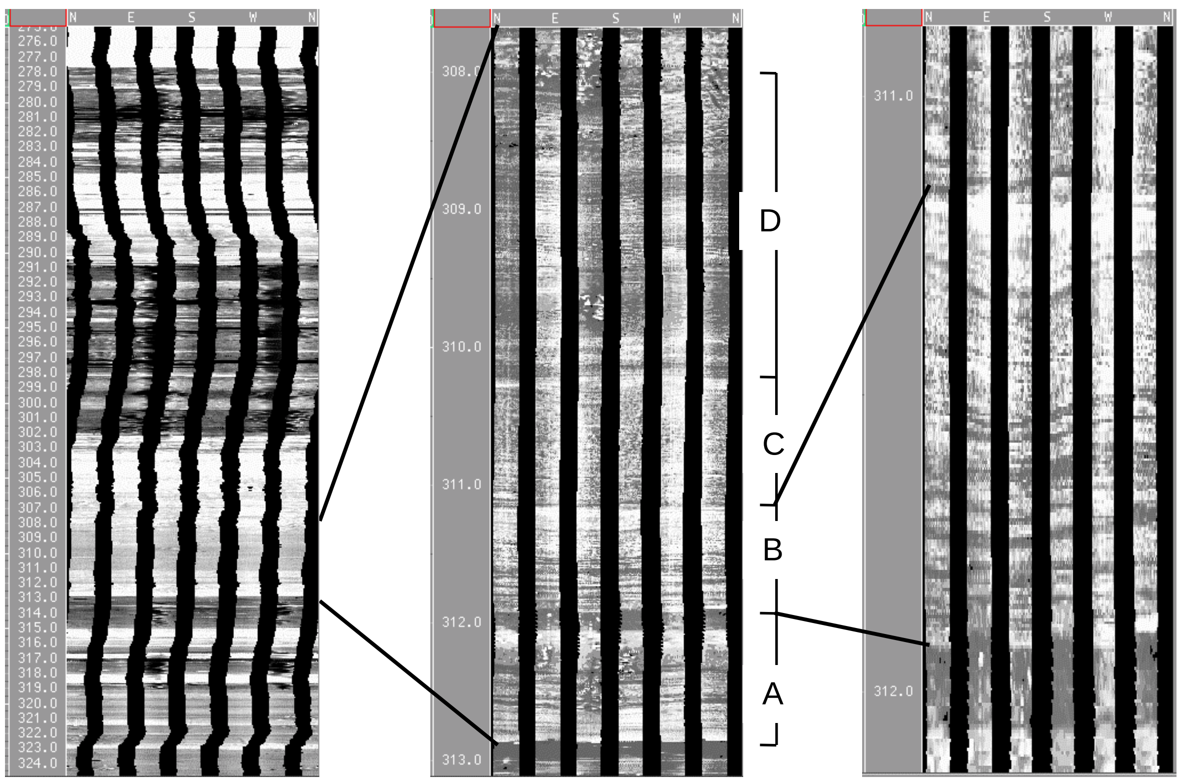

Figure 2: Electric resistivity borehole images showing a sequence of alluvial fans, successively magnified from left to right. Left image covers 50 m. Center image covers 5 m. Right image covers 1.25 m.

The left side of this figure shows 50 m of a clastic sequence consisting of sands (light color) and shaly sands (dark color). The sands have been interpreted to represent alluvial fans, whereas the shaly sands probably represent fan deltas and lacustrine deposition. An enlargement of one of the sandy intervals interpreted as fans (center) reveals several channel deposits (A, B, C, D, and others not shown), separated by erosional surfaces. The simple random-walk model may help us estimate the three-dimensional architecture of these channels. Assume now that we are interested in the shape and extent of the entire fan, consisting of many channel deposits. Successful upscaling would result in a model that provides us the same overall fan shape and size as running the original model many times, but would do so with grater efficiency, at the possible cost of loss of individual-channel detail.

In the particular case of this mdel, we can exploit some of the known properties of random walks to achieve this goal. We know that if we are far enough downhill from the source for the channel to consist of a "large" number of segments, then the channel position in a transversal cross section will have a normal distribution with a standard deviation equal to:

$$W = \sigma\sqrt{n} \qquad (1)$$

where n is the number of segments from the source, and σ is the standard deviation of the diversion of each segment.

Since we assume that each channel aggrades a fixed amount (equal to the cross sectional channel area *A* times a fraction *f*), we could also calculate the height of the fan's cross section, namely:

$$H = 0.242nAf\ /W \qquad (2)$$

Figure 3 shows the morphology of the "deposit".

It is worth noticing that the overall shape of the fan given by equations (1) and (2) is independent of both (a) the assumed statistical distribution of the diversion of each channel segment (the only dependency is on the standard deviation of the distribution), and (b) the assumed shape of the channel cross section. Although these two factors are critical if we study channel connectivity, they do not affect the overall shape of the bulk deposit. This model illustrates how in the process of scaling, some detailed assumptions may become irrelevant, to the point of being completely eliminated from the model's equations.

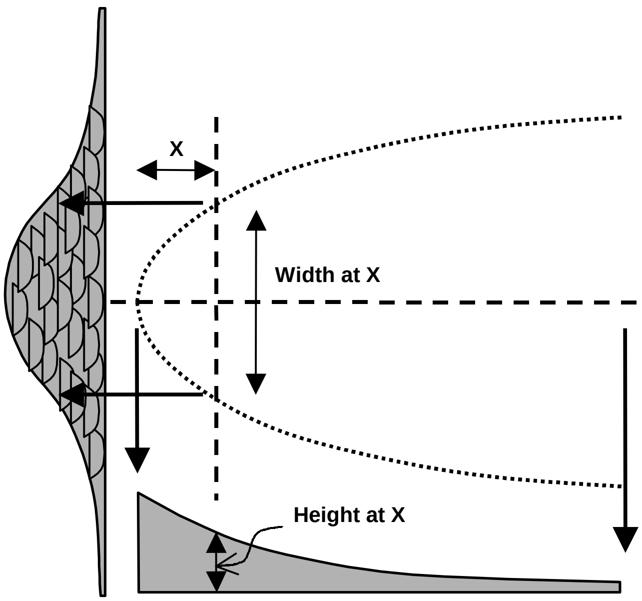

Figure 3: Bulk alluvial-fan deposit shown in plan (curved dotted line), transversal cross section (left) and longitudinal cross section (bottom).

The "scaled up" model given by equations (1) and (2) allows immediate calculation of the overall fan shape, at the cost of loss of detail of internal channel connectivity. Although this approach would save computer time if we are not interested in the internal fan architecture, it may not be sufficient for truly useful upscaling. This is because the upscaled model assumes that conditions remain constant throughout the now lengthier simulated time period. Conditions that may reasonavble assumed to be constant for a few hundred years would have to be allowed to vary if the simulation went on for several thousand years. When accounting for these changing conditions, the model becomes a fan simulator, which may in turn be upscalable.

In more complex models, one often does not count with the benefit of a well studied simple mathematical theory (such as random walks). It is thus necessary to scale the model up by experiment or by a thorough understanding of the processes.

This example also shows how to use the large-scale model for calibration. In the random-walk model, we may have had little idea of the distribution of channel cross sectional areas, aggraded fraction, and standard deviation of channel diversion per length segment. But in the bulk model, we can use the size and shape of an actual fan to calculate these parameters.

Scaling sporadic events

Many geologic systems are dominated by events that are "rare" in short time periods, but fairly certain and fundamental to the model in the long run. For example, the "thousand-year" flood may be more important in shaping the course of a river than all the minor floods that occur between these major events. Therefore, scaling a model to run over a longer period of time, may require a change in input and boundary conditions.

An example of this type of scaling to allow for sporadic events involves yearly floods in which the river level at the flood stage is assumed to follow an exponential distribution, namely:

$$f(x) = \lambda e^{-\lambda x} \quad (\mathit{for}\ x \geq 0) \qquad (3)$$

where:

x is the river level over normal stage

λ is a constant

One convenient statistic to use for the N-year flood is the median of all the maximum flood stages for N years (i.e. if we repeat the N-year experiment a large number of times, we want the gratest N-year flood to be greater than the calculated value about half of the time). For the case of the distribution given by Equation (3), this can be shown to be:

$$x = \ln(2N)/\lambda \qquad (4)$$

For example, if a river has a yearly median flood stage of 2 m (over normal stage), and the yearly flood stage has an exponential distribution, then the value of λ in Equations (3) and (4) would be approximately 0.35. The graphs for the cumulative exponential distribution and for Equation (4) would look respectively as follows:

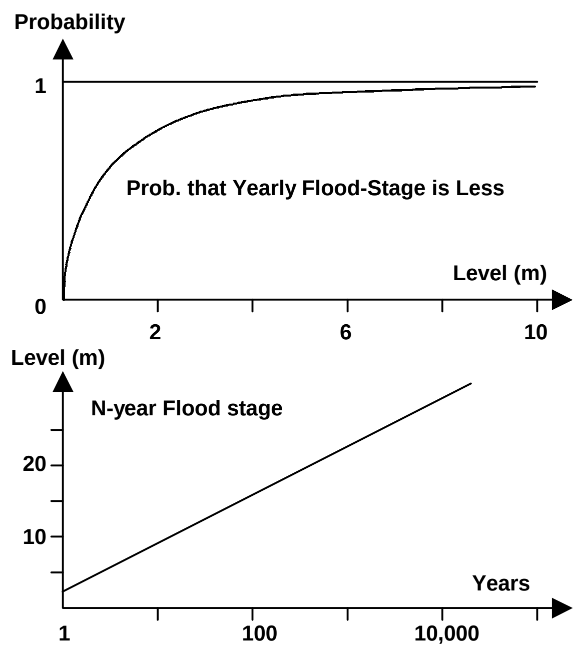

Figure 4: Top: Cumulative statistical distribution of yearly flood stage; bottom: maximum flood stage as a function of number of years.

If we simulate a period of 10 years, the largest flood would be 8.56 m (in the sense that for any 10-year period there is an equal chance that the 10-year maximum may be higher or lower than this value). If we simulate 1,000 years it would be 21.7 m. For much longer periods of time (greater than 10,000) climatic variations would have to be taken into account.

Turbidity currents appear to show less variation than the volume of river floods. A narrow log-normal distribution may be more adequate to represent the volume of each flow. Maximum rainfall, on the other hand, while distributed exponentially at any single point, must be reduced when larger areas are considered due to the nature of its spatial distribution (Linsley et al., 1975).

Fractal processes

From the early days of quantitative fluvial geomorphology, researchers have recognized that many fluvial landscapes show self affinity (Horton, 1945), while modern researchers recognized fractal behavior in fluvial sequences (Pelletier 1996). This does not mean, however that the same processes are at work at all scales. If the river channels are studied as whole systems in greater detail, self-affinity may not always hold. The uppermost tributaries, for example, are narrower than their higher–order conterparts, but tend to contain the coarsest sediments.

Some karstic dissolution processes show true self affinity that can be traced back to the processes that created them. A true self-similar or self-affine process is of course straightforward to scale, as the model needs no changes in going from one scale to a different one.

Conclusions

1. Scaling results in changes in the relative importance of some of the processes simulated by the model. When scaling up, it is often necessary to vary boundary conditions that were previously considered constant (Figure 5).
2. Scaling a dynamic model (i.e. using it to simulate times and volumes that are larger or smaller than those for which it was devised) is useful to extend the range of practical applications of the model. It also helps in understanding the model's limitations.
3. The scaling of sporadic events such as floods, rainfall, and turbiduty currents often requires a major change in the assumed intensity of these events.

References

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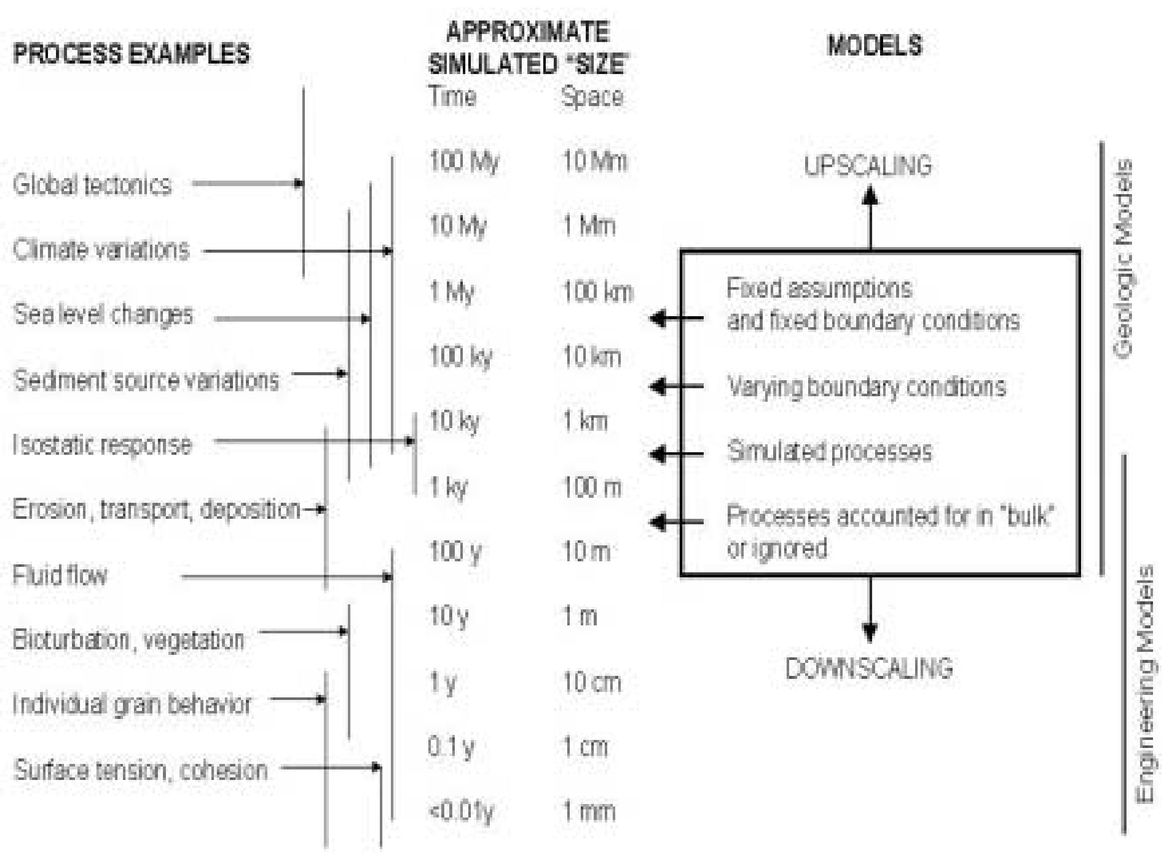

Figure 5: Schematic description of processes that operate at various scales. Depending on the scale of the model, processes may be excluded, included as fixed assumpions, as varying boundary conditions, or fully simulated.

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