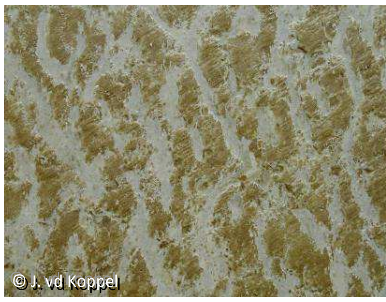


Modelling concepts in biogeomorphology

Results from presentations and discussion sessions of the workshop of 15 February 2011, Wageningen University, the Netherlands

Michel Riksen, Alma de Groot, Joep Keijsers, Ate Poortinga and Annelies Voogt

1. Introduction

Biogeomorphology (Naylor et al. 2002), also called ecogeomorphology:

> Involving ‘the cooperation between ecology and geomorphology’ to study two-way linkages between ecological and geomorphological processes.

Interactions between vegetation and landscape evolution are a growing field of interest within earth sciences. With processes acting at different spatial and temporal scales, the system’s interactions are often complex. In order to simulate complex process interactions, choices on the approach of model development have to be made. These choices are for example physically based versus cellular automata, top down versus bottom up and choices on the temporal and spatial scale. During the workshop results and progress from several biogeomorphological studies were presented and a discussion session was held about the use of different model concepts and scaling approaches. (Outline workshop see Annex 1: presentation 1 M. Riksen, 2011. *Introduction workshop 15 February 2011*). The workshop focussed on biogeomorphology of the coastal zone: intertidal flats, salt marshes and dunes.

2. Presentations

2.1. Practical and Conceptual Considerations of modeling ecogeomorphic systems using cellular automata

Andreas Baas (King’s College London)
The dune model presented (DECAL, Fig. 1) is based on a cellular automaton (CA) and developed for bare sand dune simulations by Werner, extended with vegetation components and interactions along the principles of Baas (2002). The original

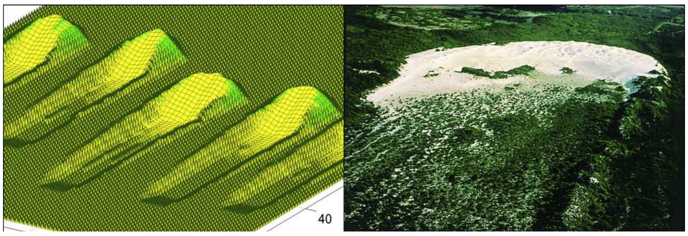
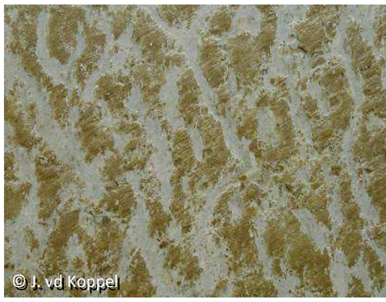


Figure 1. (Nield and Baas, 2008) (left) Simulated parabolic dunes developed out of flat blow-outs in the upwind region (lower-left side of view) after 50 years. Light-green shading indicates levels of grass effectiveness while density and size of dark-green sticks indicate levels of shrub effectiveness. Sediment transport direction from lower-left to upper-right of view. Grid resolution = 1.0 m, pe = 1.0, pd = 0.6, slab height = 0.1 m. See also animations in the auxiliary material. (right) Photograph of parabolic dune near Dongara, Western Australia, reproduced with kind permission of Patrick Hesp.



Werner model simulates a sedimentary topography composed of stacks of discrete sand slabs on a Von Neumann neighbourhood cellular grid with periodic boundaries. Slabs are picked up and moved downwind to the adjacent cell – mimicking transport by wind – and erosion and deposition of slabs are governed by probabilities (pe and pd, respectively). Two additional rules enforce the angle of repose (30°) via avalanching and a 'shadow zone' in the lee of topography where slabs are not susceptible to erosion (defined as an angle of 15° from horizontal). (See for further description of the model: Baas and Nield, 2007; Nield and Baas, 2008).

Baas explained in his presentation the main principles of cellular automata:

- Grid domain of cells with a certain variable
- Simple interactions (rules) between neighbouring cells
- Iteratively applying rules to mimic time evolution

Advantages:

- Non-deterministic
- Simple rules which makes it fast
- Emergence.

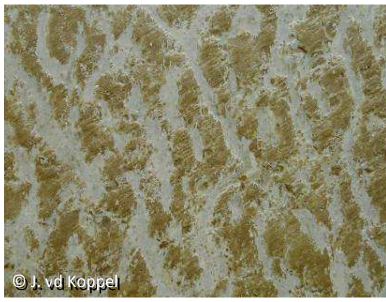
Disadvantages:

- Non-linear, can exhibit chaos
- Non-specific, stochastic
- Idealised model environments

Baas showed in his presentation the algorithm choices and their (unintended) consequences and considerations concerning the vegetation. He further explained the need for further model exploration through: sensitivity analysis on the parameters and boundary conditions; testing e.g. calibration, validation, verification, equifinality and ergodicity.

His final thoughts for the audience:

- Parameters and algorithm details need to be investigated thoroughly;
- These inquiries can lead to fundamental questions and insights;
- Many of the interesting science questions arise during model development;
- The journey is often more fruitful than the destination.



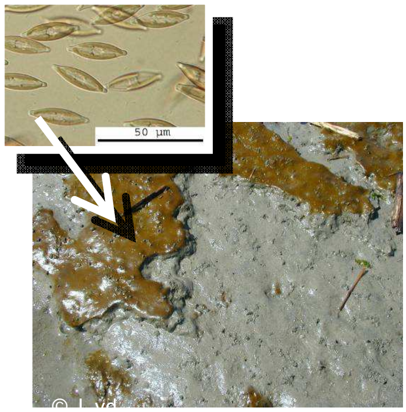
2.2. Biogeomorphological interactions on tidal mudflats

Johan van de Koppel (Centre for Estuarine and Marine Ecology, Netherlands Institute of Ecology (NIOO-KNAW)

One of the problems with bioengineering is that local feedback causes strong thresholds, unpredictability and heterogeneity at small spatial scales.

Van de Koppel gives a case study on diatom-sediment feedbacks:

- Diatoms protect the sediment from erosion
- Diatoms grow better on silt, and
- diatom losses decrease with increased silt content
- Bottom shear stress affects sedimentation and erosion.



Model predictions:

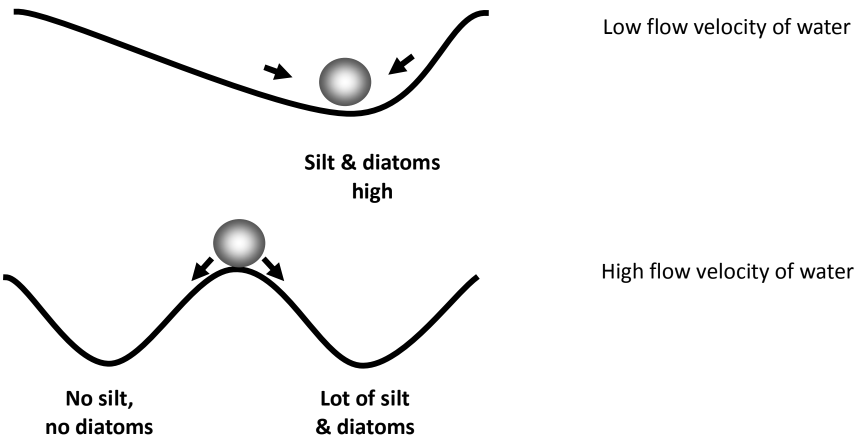
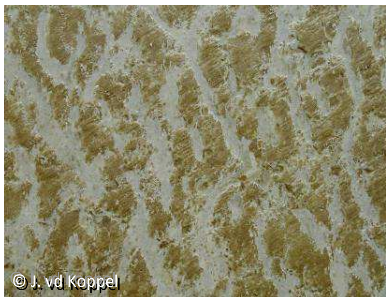


Figure 2. Stability diagrams of alternative stable stated of diatoms on intertidal flats.

Field measurements give evidence for alternate stable states! (Van de Koppel & Herman et al, Ecology 2001). The problem with alternate stable states is that both temporal and spatial scales are unknown. Timescales for the silt-diatom interaction are days to weeks, and those of seagrasses may act on the long term (but evidence is contested). Spatial scales may range from 100 cm^2 to the scale of the estuary.



<u>Model structure & assumptions</u>

- Water flows downwards: shallow water equations
- Low erosion when water layer is thin
- Scale difference: water flows on much faster time scales than diatom growth.

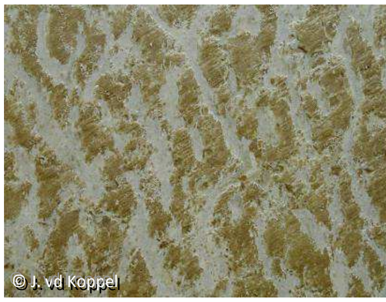
<u>General conclusions</u>

- Bioengineering affects estuarine systems at multiple spatial scales.
- Inclusion of bioengineering will generate unpredictability within hydrodynamic/biogeomorphological models, resulting from (local) bistability.
- Linear upscaling not possible.

Gap exists between ecological and hydrodynamics/morphological modeling

- Physically accurate vs. conceptual
- Large scale vs. small scale
- Aimed and prediction/understanding

=> Integration of ecological and physical modeling practices is needed!



2.3. Bio-geomorphological modelling of salt marshes

Stijn Temmerman and Wouter Vandenbruwaene (Universiteit van Antwerpen) e.a.
(presented by Johan van de Koppel)

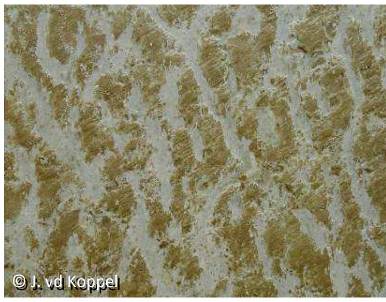
Plants growing on intertidal flats (Fig. 3) can be divided in flexible & submerged (Seagrass species) and stiff & emergent (tidal marsh & mangrove plants). The research objective is to investigate how small-scale plant-flow-sediment feedbacks are related to large-scale landscape patterns.

Figure 3. Plants growing on intertidal flats: left mangrove; middle: tidal marsh plants; right: seagrass.

Temmerman presents experimental research on small-scale plant-flow-sediment feedbacks, consisting of patches of vegetation in a flume. Vegetation leads to zones with flow reduction, resulting in sedimentation which has a positive feedback on vegetation growth. Flow acceleration on the sides of the vegetation patch leads to erosion and a negative feedback on vegetation growth.

Temmerman developed a model based on these feedback mechanisms for these two types of vegetation. From the model runs (see his presentation in Annex 3) he draws the following conclusions:

- The small-scale plant-flow-sediment feedbacks of stiff *Spartina* patches result in a large-scale bio-morphodynamic pattern of a vegetated marsh platform with channel networks.
- The small-scale plant-flow-sediment feedbacks of flexible sea grass result in a large-scale bio-morphodynamic pattern of closed sea-grass meadows without channels.



2.4. Eco-morphological modeling: An integrated approach applied in Building with Nature

Qinghua Ye (Deltares)

Ye presented the approach taken in Delft for modeling biogeomorphological systems, as related to the work within the Ecoshape/Building with Nature consortium.

The importance of biological effects in morphological modelling is that ecological processes of both vegetation and other biota affect morphology at various scales. These effects are on tide propagation, tide asymmetry, sediment entrainment, transport, deposition, morphology change, turbulence intensity and wave energy.

Bio-morphological modeling will therefore be used for eco-dynamic design.

Ye showed the effect of vegetation on bed level development for a case study consisting of a 400 m × 700 m, bare sandy mildly sloping tidal basin. Figure 4 shows the model results, left without vegetation and right with *Spartina-like spp,* on the formation of channels.

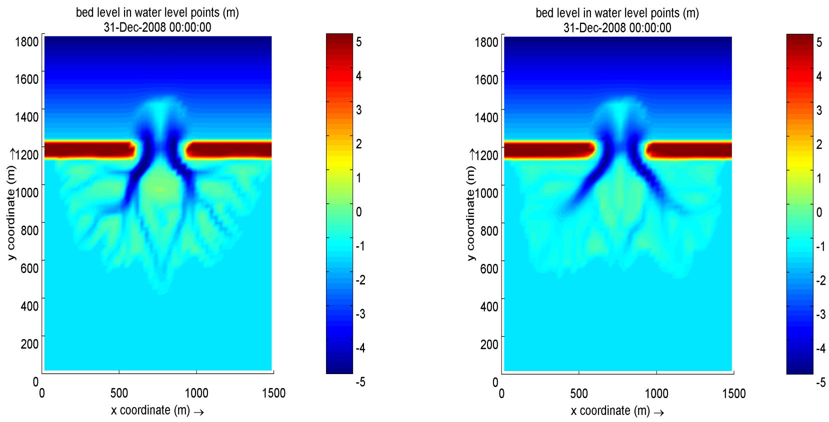


Figure 4. Simulations of a bare (left) and vegetated (right) tidal channel and flat system.

The integrated approach of Delft consists of a process-based modal in which the following processes are coupled with different individual timescales (Figure 5):

- Hydrodynamic processes
- Sediment transport processes
- Morphological processes
- Ecological processes and scales

Ye explained how the different models are couples in relation to their time scales:
Figure coupling of scales (after de Vries, 2007)

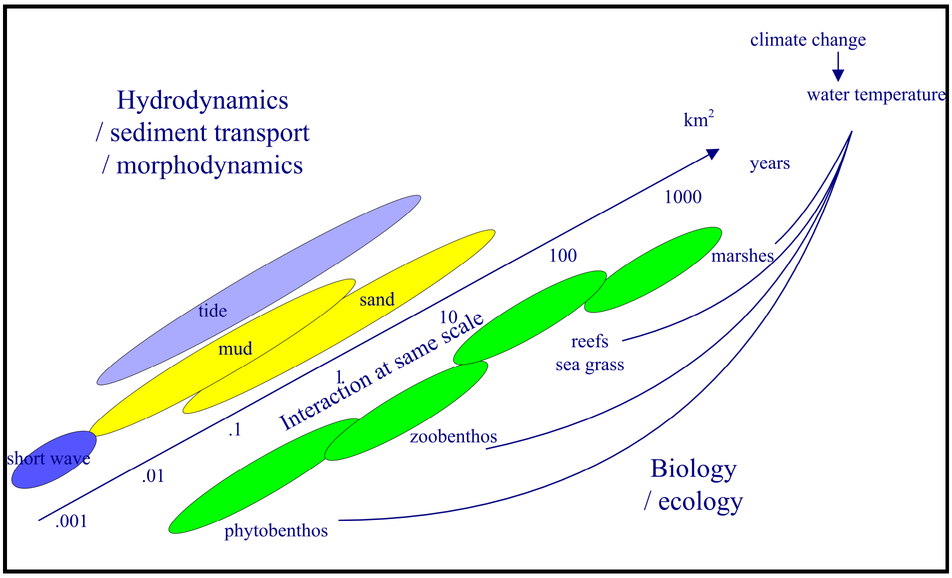
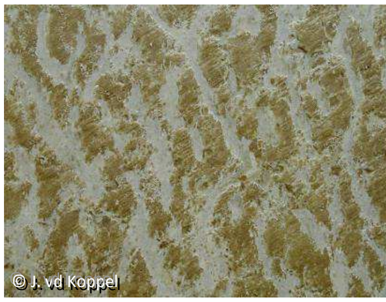


Figure 5. Scale coupling (after de Vries, 2007)

In his presentation Ye further discussed the effect of vegetation on the different landscape forming processes, and showed several examples of model approaches for different field situations.
Main conclusions:

- Bio-geomorphology modeling involves linking processes at proper scales. It is possible to model them by coupling the processes in a proper way;
- Choosing proper scales to couple is a crucial question to be answered before modeling is carried out;
- An new integrated approach is applied in Building with Nature for eco-morphological modeling practice;
- Tight incorporation is necessary.



3. Discussion session

The discussion session in the afternoon was introduced by a presentation by Alma de Groot, Ate Poortinga and Joep Keijsers in which they gave a short overview of their research project and the problems they face with modelling. They are currently working on a field- and model-based study on sand transport, the formation of coastal dunes and associated vegetation development on various temporal and spatial scales. The fieldwork consists of measurements of sand transport, surface moisture, wind parameters, topography and vegetation characteristics. The modelling consists of the adaptation and integration of three existing models: WEPS for sediment erosion, transport and deposition, DECAL for dune formation and NUCOM for vegetation development. The final model will be used for assessing the impact of climate change and coastal management on dune and vegetation development.

Three main discussion themes were posed for the group discussions:

1. interaction bio – geo
2. scale issues
3. top-down – bottom up

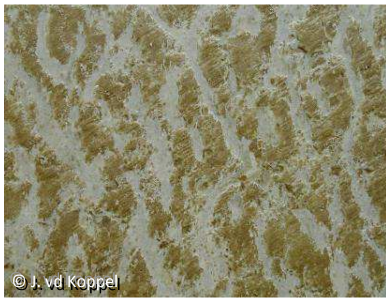
The topics were first discussed in three groups. The discussions were started from a number of statements per theme (given below), but also other ideas were discussed. Finally, the outcomes of the group discussions were presented and discussed plenary.

<u>3.1. Bio-geo interaction</u>

There were four statements that that were used to start the discussion. None of these statements were considered entirely true and the resulting discussion gave rise to a number of thoughts.

<u>3.1.1. Parameterisation of the bio-geo interaction is most important.</u>

Parameterisation is always an important factor in any model development and the model itself may give insight in what the most determining parameters are. Because biogeomorphology is a relatively new field, there is a lack of data on the interaction itself between the geo and bio components. Moreover, as most researchers come from one of the two fields (is there a university study on biogeomorphology? Earth System Science at WUR perhaps?) the focus of experiments and measurements tends to be driven by their field. When a model needs to be parameterised or tested, chances are that the interaction needs most attention. Next to the demand for more data there is a wish for a more integrated approach to obtaining these data.



3.1.2. Ecology is most suited for explanatory models and geomorphology for predictive models.

It is not so black and white: both geomorphology and ecology have explanatory and predictive models. Whether a model is mainly explanatory or predictive depends on its aim, which can be driven by things like academic curiosity or the client (such as the government). This overrules differences in disciplines that may exist in the degree of conceptual thinking that is done. The impression at first was that ecology tends to use more concepts than geomorphology, but there are many subfields for which this is not valid.

3.1.3. Biogeomorphological models are more site-specific than mono-disciplinary models.

Modelling aims at reproducing processes that are universal, both in geomorphology and biology/ecology. Adding linkages therefore merely potentially increases the number of parameters. As long as the parameter values are properly adjusted, the model should be generally applicable. Climatic zones create the most obvious differences between biogemorphological systems, but some of this difference is removed because different organisms may fill the same niches in different climatic zones.

3.1.4. Biogeomorphology models face different challenges than other models.

Most of the model challenges identified in this discussion and in the preparation for this workshop apply equally to other mono-disciplinary models. In biogeomorphological models, scale issues are particularly important. The time and length scales of vegetation and geomorphological processes may differ considerably, while still influencing each other. An example are the large fluctuations in sand transport on coastal dunes on the daily timescale that may or may not affect vegetation growth on the scale of months or years. A possible way to approach this is to look at characteristic adaptation times or lengths and use these as the resolution at which the bio and geo processes interact (this relates to the discussion of statement 1 scale issues).

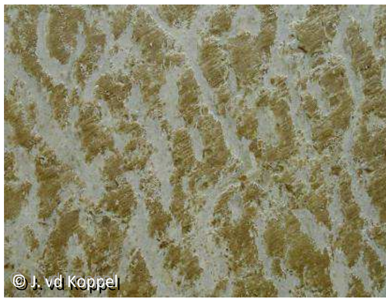
3.1.5 Other issues

A model is only truly biogeomorphological if it incorporates the feedback between the biotic and geomorphological components, i.e. the influence of the one on the other and also the other way round. Examples that were given are:

- dune vegetation influences sand transport, but its growth is in turn affected by the amount of sand eroded or deposited;
- Vegetation growth depends on groundwater level and salinity, but transpiration by the plants affects groundwater level and salinity.

A model that does incorporate both but is not biogeomorphological is for example a river model that includes vegetation only as roughness element and does not include the response of the vegetation.

We always came back on scaling issues. Many things depend on at which scale you are looking.



As biogeomorphology is an interdisciplinary science, it costs time for researchers to get familiar with both underlying fields. This may be a drawback.

Are all systems subject to bio-geo interaction? Biota exert their influence on the interface between the Earth's internal forces and external forces, and may therefore form interactions with both. Is life imprinting a signature on landform on all spatial scales, i.e. are there scales so big that biota are not important? And do biota constrain the sizes of spatial patterns (work by Baas; Dietrich & Perron, 2006)? It looks like biota are always important, e.g. taking the example by Andreas: vegetation affects soil stabilisation and thus denudation rates at mountain ranges, denudation rates affect mass distribution on continents, which affects plate tectonics, which affect climate, which affect vegetation. Flipping the question backwards: are there landforms that cannot be made without life? That if you see them from space you'd known there is life there? We discussed salt marshes, with their typical channel patterns that are stabilized by vegetation (e.g. Temmerman et al., 2007). Johan: The same sinuosity you can also see on (muddy) tidal flats, but there they generally have larger magnitude and are less stable.

3.2. Scale issues

3.2.1 The grid size of a biogeomorphological model should be defined by the size of the smallest feature under consideration.

Not only the smallest feature is important, but also the scale of the studied processes, size of the study area, resolution of the input data and the aim of your model. Depending on the focus of your model, some processes or features can be neglected. The grid size should be sufficiently small to represent the smallest remaining processes or features.

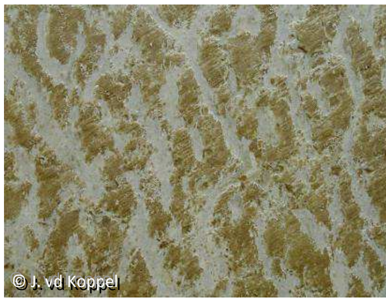
Results of physically based models are thought to be independent of the grid size, whereas in most rule based models the grid size is an important parameter. Does this mean rule based models should stick to explanation rather than prediction?

3.2.2 It is easier to predict developments at micro or macro scale than at meso scale.

Background of the statement: at micro scale, a lot of factors can be excluded because only a single process or feature is considered. At macro scale, small scale variability can be neglected and long term trends dominate. At meso scale, interactions between processes of different scales are prominent, making it more difficult.

In the discussion, no common idea of micro, meso and macro scale was found. Whatever scale you are considering, there is always a smaller and a larger scale. Modelling across multiple scales is most difficult: the problem of biogeomorphology. An important risk of mixing scales is that factors that are constant on one scale are variable on other scales. Careful nesting may solve some mismatches in the scales.

3.2.3 Small scale field measurements are of little use to large scale modeling.



Small scale field measurements can at least give you an idea of the magnitude and variability associated with the processes in your model. Field observations (data) are necessary for both understanding of a system (the basis for developing a model) and running a model. These three components are essential if predictions need to be made.

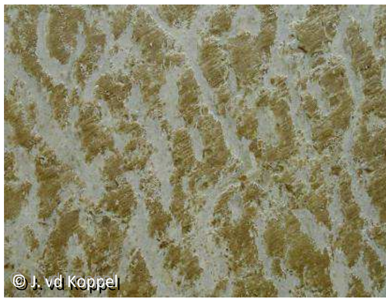
If sufficient measurements are taken, they can be used to restrain the important parameters as much as possible. A sound field strategy is important to get the most out of the measurements, e.g. sampling at key points, or in a grid, setting up a sampling routine to account for temporal variability. Whether you want to include variability depends on the goal of your model and the resources available.

Do field work requirements differ for explanatory models and prediction models?

<u>3.2.4 Long term model behaviour cannot be validated.</u>
The common way is to perform hind casting, by using inferred history (e.g. from stratigraphy or pollen records) as future. Another way is space-for-time substitution: compare study sites that are topographically similar, but subject to different environmental conditions. <u>General remarks</u>
In the group discussion about bio-geo-interactions, the recurring phrase was 'scale issues', because choices in a biogeomorphological model depend on the scale you are considering. During this discussion, the *aim* of the model was repeatedly named as factor on which decisions depend.
Any model development should start with a clear question, which leads to how the system should be approached, which components are of importance and what model type is most suited.
Some models may be suited to answer several questions (e.g. focus on vegetation growth or focus on dune formation) and the same question may give rise to different model approaches (e.g. dune formation using CA model (Baas & Nield, 2007) or fluid dynamics (e.g. Luna et al., 2009)).
although the same question may give rise to different model approaches (e.g. dune formation using CA model (Baas & Nield, 2007) or fluid dynamics (e.g. Luna et al., 2009)).

3.3. Bottom-up – top down

<u>3.3.1 The different processes acting on different scales make it impossible to integrate top-down bottom-up approaches.</u>
To answer this question it is important to define the goal of the model. Bottom up approaches are associated with studying the small scale processes. Top down approaches might be more useful for larger processes, but this is not always truth. It is important to define what we want and which components are necessary to accomplish this goal. When we are talking about integration of top down and bottom up it might be useful to translate physical rules into behavioral rules. For example: if we want to run DECAL with physical information (e.g. windspeed), the physical information should be

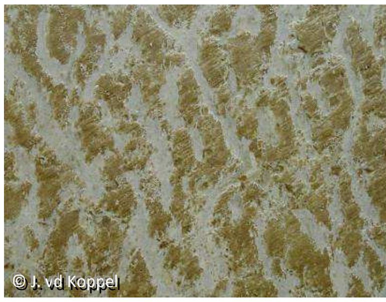


translated into parameter values which leads to different bedforms with different windspeeds. It is recommended to draw an scheme to determine the processes that are needed.

Can a top-down model be combined with a bottom-up model? No, but you can use parts of both models and use them in a new model. There was some confusion about what a top-down approach entails and if for example the DECAL model is a top-down model or not. Reduced-complexity might be a better description. Quoting Wikipedia (although not so scientific, yet a rather clear description): http://en.wikipedia.org/wiki/Top-down_and_bottom-up_design

3.3.2 Chaos should be integrated in every modeling approach to determine the context of the results.
This statement was a little bit confusing for some participants, as they always try to eliminate the chaos from their models. The chaos referred to in this context is how to cope with unexpected changes, as can happen in real world systems. It was suggested to perform sensitivity analysis and monte-Carlo simulations to explore the parameter space. Chaos was also referred to as unexpected chaotic behavior of the model. Model structure and parameter space is also important in this context. Chaotic behaviour is something that is a property of a model. It means that with small variations in input (starting conditions, boundary conditions or parameters) the model outcomes vary wildly. This is not necessary a desired model property, even though it is thought to be a property of e.g. weather systems. What is meant here is that input parameters have a certain uncertainty or probability distribution, which will propagate through the model and affect its outcome. This can be investigated using an uncertainty analysis. Uncertainty analysis is slightly different from a sensitivity analysis, in which the effect of variations of input parameters on model outcome is tested, where these variations are not related to parameter uncertainty.
The random properties of parameters and processes are incorporated in stochastic models as for example cellular automata.

3.3.3 Most physical based model in (bio)geomorphology studies can also be considered stochastic or empirical.
The outcome of this discussion was that all physical based models contain some empirical considerations at some points. Even physical based models using the navier-stokes equation contain eddy closures at some point, not representing the inherent physical properties. Physical based model can be considered as stochastic if they contain a random number generator at some point in the model. If this is not the case, the whole model is deterministic and does not contain any stochastic components.



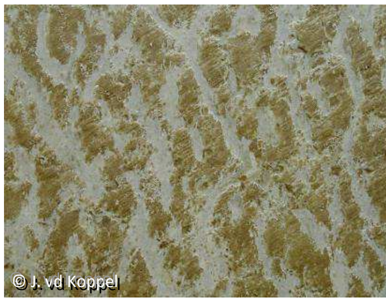
“Top-down and bottom-up are strategies of information processing and knowledge ordering, mostly involving software, but also other humanistic and scientific theories (see systemics). In practice, they can be seen as a style of thinking and teaching. In many cases top-down is used as a synonym of analysis or decomposition, and bottom-up of synthesis.

A top-down approach (is also known as step-wise design) is essentially the breaking down of a system to gain insight into its compositional sub-systems. In a top-down approach an overview of the system is formulated, specifying but not detailing any first-level subsystems. Each subsystem is then refined in yet greater detail, sometimes in many additional subsystem levels, until the entire specification is reduced to base elements. A top-down model is often specified with the assistance of "black boxes", these make it easier to manipulate. However, black boxes may fail to elucidate elementary mechanisms or be detailed enough to realistically validate the model.

A bottom-up approach is the piecing together of systems to give rise to grander systems, thus making the original systems sub-systems of the emergent system. In a bottom-up approach the individual base elements of the system are first specified in great detail. These elements are then linked together to form larger subsystems, which then in turn are linked, sometimes in many levels, until a complete top-level system is formed. This strategy often resembles a "seed" model, whereby the beginnings are small but eventually grow in complexity and completeness. However, "organic strategies" may result in a tangle of elements and subsystems, developed in isolation and subject to local optimization as opposed to meeting a global purpose.”

Acknowledgements

First we like to thank all the participants for their contribution to this workshop. Special thanks go to the keynote speakers Dr. Andreas Baas, Dr. Johan van de Koppel and Qinghua YE. and Dr. Stijn Temmerman (whose work was presented by Johan van de Koppel).
The workshop was co-financed by the research school PE&RC . We specially like to thank Claudius van der Vijver and Carmen Carcelen Rivera of PE&RC for their support in the preparation of the workshop.



References

Baas, A.C.W., Nield, J.M., 2007. Modelling vegetated dune landscapes. Geophysical Research Letters, vol. 34, L06405, doi:10.1029/2006GL029152.

Dietrich, W.E., Perron, J.T., 2006. The search for a topographic signature of life. Nature, 439(7075), 411-418.

Luna, M., Parteli, E.J.R., Duran, O., Herrmann, H.J., 2009. Modeling transverse dunes with vegetation. Physica a-Statistical Mechanics and Its Applications, 388(19), 4205-4217.

Nield J.M. and Baas, A.C.W., 2008. The influence of different environmental and climatic conditions on vegetated aeolian dune landscape development and response. Global and Planetary Change 64: 76–92.

Temmerman, S., Bouma, T.J., Van de Koppel, J., Van der Wal, D.D., De Vries, M.B., Herman, P.M.J., 2007. Vegetation causes channel erosion in a tidal landscape. Geology, 35(7), 631-634.