Use of a nested modeling framework to study multiscale hydrological processes

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ABSTRACT: Within hydrology the trend is to integrate different mathematical models coming from related disciplines. These models operate most often on different scales. Therefore, there is a need for a modeling environment in which stand-alone models can operate simultaneously on the corresponding scales with possible cross-scale interference. We propose a framework that takes advantage of the inherent nested spatial character of hydrological processes and lets the process knowledge exactly operate on the scale it was studied. We show that with this multi-scale framework, nonlinear hydrological response can be simulated and argue that using a nested modeling strategy, our understanding of hydrological response can be improved and cross-scale interaction of multiscale controls can be investigated.

1 INTRODUCTION

Especially hydrology is a multi-disciplinary field of study with observations and model descriptions on different scales. Scale-issues create a challenge for many hydrological scientists as it is inevitable to link observations and models on different scales (Philips, 2005). When process knowledge and observations are transferred to a mathematical model, scientists tend to focus on just one scale supposing that the 'first principles' or the main driving forces processes reside on one specific scale (Blöschl 2001). As a consequence, in hydrological modeling studies a-priori assumptions are made about the cross-scale linkages of processes. Most hydrological models are scale-dependent (Reed et al. 2004), hence no insight can be obtained through the modeling analysis about how processes influence each other across scales and how scale-specific nonlinearities and thresholds affect other scales.

Besides, the tendency in hydrological modeling is to couple model descriptions coming from different related disciplines (e.g. European OpenMI project). This implies inevitably having to deal with scale-issues. Scale problems are found for example in the coupling of overlandflow and routing models with sediment and chemical transport models (e.g. Simpson and Castelltort, 2006).

One of the biggest challenges in hydrological studies in is dealing with nonlinearities and thresholds. Nonlinear system response is thought to be related with patterns and multiple controls acting on multiple scales (Sivapalan, 2005). The influence of nonlinearities and thresholds on a certain scale on the system response has been studied in field- and modeling studies (e.g. Kokkonen et al. 2004). Especially in semi-arid areas, the nonlinear relationship between rainfall and runoff makes the modeling process more complex (Ye et al. 1997) and nonlinear (Goodrich et al. 1997).

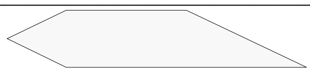
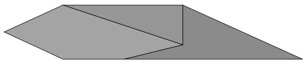
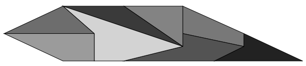
In hydrology, nested approaches can be found in field and theoretical studies (e.g. Cammeraat, 2004); however, in modeling little has been done so far. The semi-distributed approaches (e.g. HEC-HMS) can be considered close to nested modeling but no real nesting on different hierarchical levels with different model descriptions is possible. A promising hierarchical approach is the use of spatial object hierarchies in GIS (Band et al. 2000).

This study proposes a nested modeling framework through which different scale-dependent hydrological models are able to operate simultaneously on different scales and communicate with each other. The framework counts with a hierarchical tree structure for the state variables and model parameters of the different models. This data structure makes use of the nesting capabilities of cell and structure arrays in MATLAB. Every hierarchic level in the data structure corresponds to a scale-level and every node to one of the spatial model elements. To every scale-level one or more models can be applied.

2 FRAMEWORK CONSIDERATIONS AND DETAILS

The notion we have of the hydrological structure of a watershed is an interconnected network of streams with contributing areas on both sides, resulting in a mosaic being composed of many nested sub-catchments. This nested hierarchy and the relation between the spatial and temporal scale are the main piles of the modeling framework. Some framework concepts are schematized in Table 1.

Table 1. Illustration of framework concepts: the scale domain is discretized in scale-levels, each one having corresponding spatial and temporal boundary values and 1 or more models applied to it.

Scale-level	Spatial discretization	Timestep	Models
1		1 year	Model X & Model Y
2		1 day	Model Y
3		1 min	Model Z & Model W

Besides coordinating the output analysis and visualizing the data, the framework accomplishes three main tasks; shortly commented in the following sections:

2.1 *Multiscale time frames*

The framework functions as a manager handing out the jobs to his workers and tells the models between which two time instants the job has to be finished. Within these temporal boundary values, the models are able to work with their own timesteps. The framework uses a dynamic function with a recursive algorithm that handles the different scale-dependent time intervals.

2.2 *Data transfer to the models*

The framework provides the models with the correct data of the spatial model elements. This task requires a common data structure in which the state variables and model parameters of the different models can be stored. The data structure needs to preserve the multi-scale and multi-model character of the framework. Therefore, a so-called tree cell array was designed in MATLAB, forming the backbone of the framework. For every scale-level it passes the right model parameters and state variables to the models. This approach has the advantage that every spatial sub-element can be taken by the models as an autonomous functional sub-watershed.

2.3 *Inter-model communication*

One of the main objectives of the framework is to offer a clear communication structure to the models. The framework counts with the necessary message functions that exchange and update data with the tree cell array. It has to be noted that the modeling framework already passes directly the right parameters and variables to the models for every timestep. Only when inter-model communication is necessary, these function calls are required.

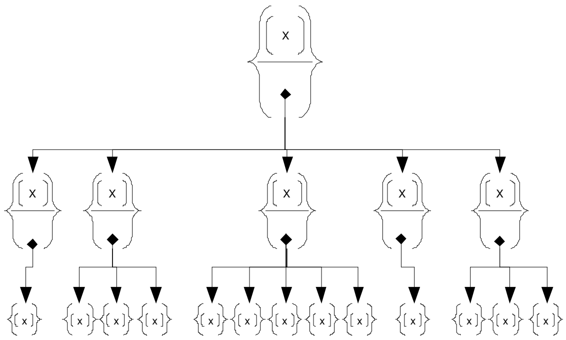


Figure 1. Schematic representation of a tree cell array with three nested hierarchic levels. The brackets {} represent nested cell arrays and [x] symbols the arrays with the data.

3 CASE STUDY: A NESTED OVERLANDFLOW MODEL

A basic multiscale framework application was carried out to show the capability of the framework to reproduce a nonlinear system response. Two models were implemented in the framework, one being a simple description of Hortonian overlandflow, and the other of detention storage on different scale-levels. No calibration or comparison with real data was done as the only objective was to test whether the behavior of the system.

Three scale-levels were distinguished. On the finest scale-level both models were applied (infiltration and detention storage) and on the other 2 coarser scale-levels only the detention storage model. The case study uses an arbitrary spatial discretization with the corresponding tree cell array having 1 element on the first scale-level, 10 elements on the second and 100 on the 3rd scale-level. These elements were randomly connected with each other (similar to figure 1).

The infiltration model is based on the Green-Ampt function:

$$f = A + \frac{B}{S_i} \tag{1}$$

in which f is the infiltration capacity, A and B are constants and S_i the infiltrated water volume.

The detention storage model consists of a conceptual bucket for every spatial model element, of which the outflow can be described as:

$$Q = \frac{\max(S_d - S_{d,\max}, 0)}{\Delta t} \tag{2}$$

in which Q is the outflow, S_d the detention storage volume, $S_{d,\max}$ the maximum storage volume and Δt the integration timestep.

The relation of the input magnitude of the system with the output response was examined multiplying a 60-timestep design rainfall record with different scaling factors. This was compared with the system output being the overflow of the detention storage element on the coarsest scale-level.

Figure 2 shows the input variable (rainfall intensity) and the output depending on the input magnitude. The system starts to react with a relative magnitude of 0.4. The output is clearly non-proportional to the input in terms of volume and amplitude of the output dynamics. The system shows a strong and fast transition being the result of the cumulative effects of the finer scale system controls.

4 CONCLUSIONS

The framework counts with a hierarchical tree data structure with the corresponding interface functions. The main advantage of this tree data structure is its flexibility for multiscale discretizations and the fact that it is capable to retain the nested hierarchy of hydrological processes itself.

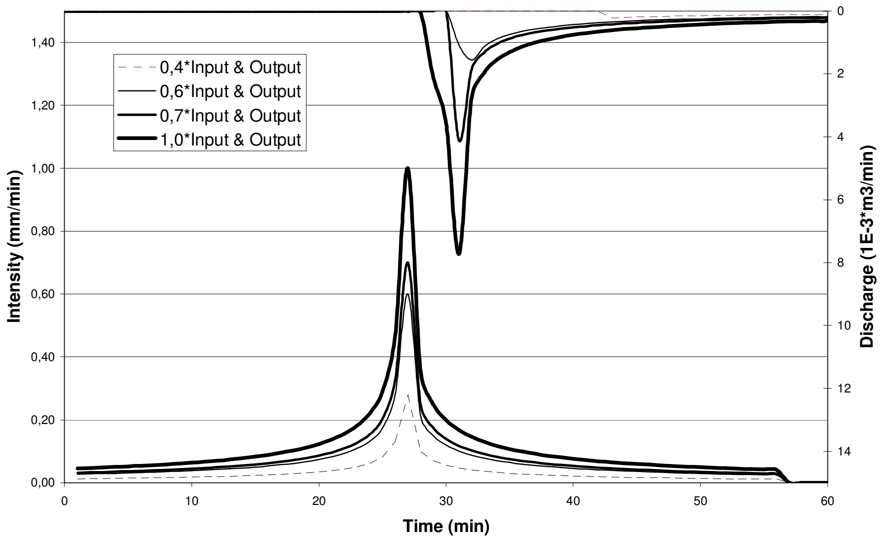


Figure 2. Comparison of the system output with varying input magnitudes.

The framework assigns to every scale-level a different temporal discretization. Within these time frames, the framework passes exactly the information of the right node in the data tree to the models. Inter-model communication is possible through a message-type function of the framework.

To test the framework, a simple application was done with two models related to overlandflow. Due to the multiscale character of the system with threshold controls acting on different scales, nonlinearity was demonstrated between input magnitude and response dynamics.

The next step in the investigation will be the development of an experimental design for the observation input parameters in order to carry out a real application of the framework. The questions that will have to be answered is how to make use of hierarchical measurements and how to perform a multiscale calibration. This study indicated that a nested hydrological modeling framework can serve as an intuitive tool for the coupling of multiscale models and studying nonlinear hydrologic responses.

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