Development of an extended spatially distributed routing scheme and its impact on process oriented hydrological modelling results

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Abstract Fully spatially distributed hydrological modelling requires a topological linkage of single modelling entities (e.g. hydrological response units – HRU) in order to reproduce relevant attenuation and translation processes within the stream, but also during the transport of water in the form of lateral surface or subsurface flow. Most often such linkage is considered by a one-dimensional (1-D) approach which links one modelling entity to only one receiver that follows the flow direction. The comparison with actual lateral water movement in catchments show that such a 1-D routing scheme is often too simple, which can lead to an overestimation of the runoff concentration along the 1-D flow paths. On the other hand, an underestimation of runoff in flow cascades that do not reside next to the main 1D flow paths can occur as the affected HRUs do not receive realistic inflow from their source entities above. As a catchment-wide consequence the 1-D routing scheme can result in a significant over- or underestimation of the contributing area for specific parts of a catchment, which can have important implications for the spatial distribution of accompanying processes such as spatial variation of soil moisture, soil erosion or solute transport. To address the problems outlined above, a new approach has been developed that allows a multi-dimensional linkage of model entities in such a way that each entity can have various receivers to which the water is passed. This extended routing scheme was implemented in the hydrological modelling system J2000 (Krause, 2001) and was used for the simulation of the hydrological processes of a number of meso-scaled catchments in Thuringia, Germany. The paper presents the most important details of the extended routing scheme, the simulation results along with the comparison of those obtained with the 1-D linkage and highlights the impacts on the hydrological process dynamics as well as on the HRU-based mass transport and balancing.

Key words hydrological modelling; routing scheme; multi-dimensional linkage; HRU; model entities

1 PROBLEM STATEMENT

Because of an insufficient hydro-meteorological infrastructure in many catchments, the time series required for hydrological modelling, such as discharge and precipitation data, are not available. Furthermore, most often the elevation data of the *Shuttle Radar Topography Mission* (SRTM) is the only spatial data available on a high resolution. To satisfy the need to include these catchments in planning of water management, it is essential to tap the full potential of this data source and to completely understand the impact of relief on researched hydrological processes. In addition to the improvement of relief-based derivation of HRUs, the topological linkage of these also plays a prominent role.

The focus of the work presented lies on the extension of the approach of Staudenrausch (2001) for the derivation of topological relations between hydrological modelling entities. This approach extended the HRU concept of Flügel (1996) by integrating the stream network into the overall topology as well as structuring the single HRUs hydrologically and topologically. Thus, this approach forms the basis for the simulation of runoff relevant attenuation and translation processes within the stream and the accurate treatment of lateral water flows between adjacent sub-entities. The linkage between the modelling entities is established through the point of maximum flow accumulation within each HRU by providing the whole simulated runoff as input to the next HRU (Staudenrausch, 2001). The one-dimensionality of this HRU linkage approach leads to the same problems resulting from the application of one dimensional (1-D) flow direction methods on raster level (Tarboton, 1997; Tarboton & Baker, 2008). On the one hand, the contributing areas along the 1-D flow paths can be highly overestimated, which leads to an accelerated runoff concentration. On the other hand, no inflow from the upslope area is simulated in the flow cascades which are adjacent to the 1-D flow paths. This has a strong impact on the processes which are directly related to the contributing area. Different studies (Pan *et al*., 2004; Zinko *et al.*, 2005) showed that multiple flow direction methods allow more accurate simulation than 1-D approaches. That is mainly essential for processes that assume broad sheets of rapidly flowing water filled with sediment, such as in the case of sheet erosion (Tetzlaff, 2006). The same issue is emphasized by Sørensen *et al.* (2006) regarding the emulation of the spatial distribution patterns of certain measured hydrological variables, such as groundwater levels and the spatial distribution of soil moisture.

2 RESEARCH OBJECTIVES

The demands for an extended approach for the derivation of hydrological topologies can be summarized as follows: a linkage is required in which: (i) single modelling entities are able to drain into more than one adjacent entities or flow segments (1:*n* relation) without (ii) breaking the concept of *hydrological response units* (HRUs).The original boundaries of the HRUs should be conserved in order to maintain the process oriented character of the concept. Furthermore, (iii) so-called circle flows be avoided, i.e. the runoff of one HRU is not allowed to flow back into the same HRU while running through the flow cascade, because this water is not forwarded to the catchment outlet. This is due to the way the runoff forwarding is implemented in physically-based catchment models, such as J2000. When the model is initialized and the hierarchy of HRUs within the flow cascade, the so-called topological hierarchy is set. According to this order, the runoff is calculated starting from the upper catchment areas to the river stream. The resulting runoff shares of each HRU are forwarded to the storage of the HRU, which is situated downslope and modifies the storage content for the following calculations. An advantage of this approach is that the dissemination of water within one time step is not dependent on the number of HRUs. A presupposition for a precise runoff calculation is that one HRU has already received the complete runoff from the upper entities when it is processed. Circle flows, so-called circular dependencies, do not fulfil this requirement, because the input to an entity depends on its own runoff elsewhere.

3 METHODOLOGY

3.1 Determination of flow relations

A flow relation between two adjacent model entities exists when one entity drains either partly or completely to the other entity. Mathematically the relation can be expressed as the edge of a directed graph to which a certain value is assigned that represents the weight of the overall runoff of an HRU (node). The derivation of flow relations as well as the calculation of their weight is carried out in a GIS. Based on an analysis of the flow direction grid, the grid cells from the HRU sample are extracted that drain across the borders to another HRU (Fig. 1, left side). For each of the extracted grid cells the size of the specific catchment area, i.e. the area which contributes to the runoff, is calculated. The specific catchment areas of those grid cells that drain to the same HRU are aggregated and compared to the overall contributing area of the HRU. In that way the proportion of the overall runoff of an HRU can be calculated for every flow relation (Fig. 1, right side).

The specific catchment area is suitable for the calculation of weights, because it incorporates the position of the flow relations within a runoff cascade and therefore reproduces the water which actually flows through an HRU.

3.2 Identification of circle flows

Circle flows represent cycles within the graph, e.g. an edge sequence where starting and ending node are identical. This leads to circular dependencies within a flow cascade, because the runoff of one HRU reaches the same HRU again when running through the cascade. Thus, a topological sorting of the modelling entities, as discussed in Section 2, is not possible. Therefore, the

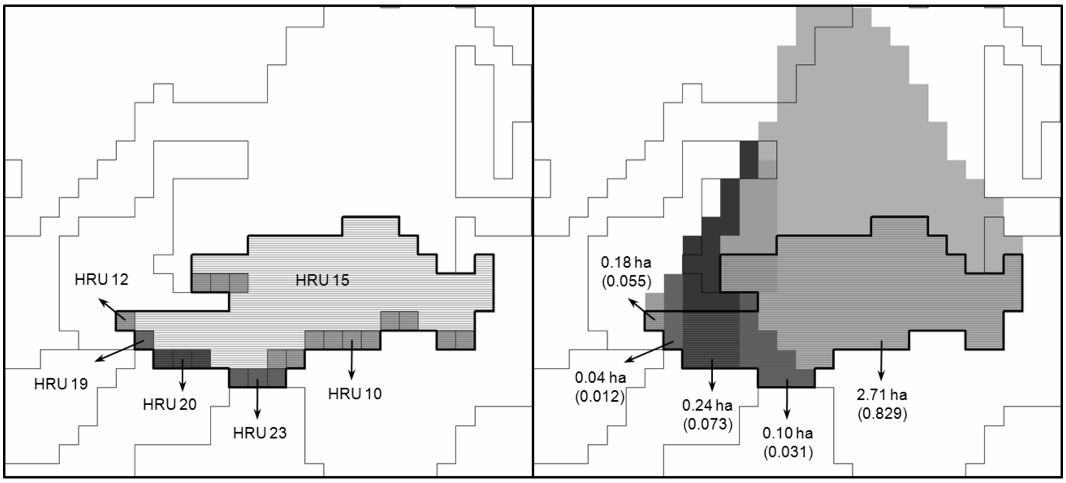

Fig. 1 Derivation of more dimensional flow relations. Left: Extraction of all grid cells which drain to another HRU. Right: Calculation of the weight of the flow relations from the specific catchment areas.

identification and dissolving of the circle flows is mandatory. Accordingly a new module has been implemented into the modelling system J2000, which finds and dissolves circle flows.

For the identification of circle flows it is necessary to make the flow path of the water through the catchment traceable. That is why the vertices-edge-structure is analysed completely. The algorithm implements a so-called depth-first search. A benefit is that only one search path is stored in the stack, which is read when a circle flow has been identified. Starting from each HRU, the neighbours to which a flow relation exists are searched for. These areas are then stored in a queue. Starting with the first node in the queue, the search depth is increased and the path is stored in a stack. This procedure is repeated until the flow relation points to river segment or reaches a certain area for the second time. If this area is equal to the starting HRU, a circle flow has been identified. Otherwise the algorithm returns to the last intersection (backtracking) and another path is searched until one of the aforementioned abort criteria occurs. The search is continued until no more vertices exist, that are reachable from the starting HRU.

Figure 2 depicts the procedure schematically for several modelling entities in an area.

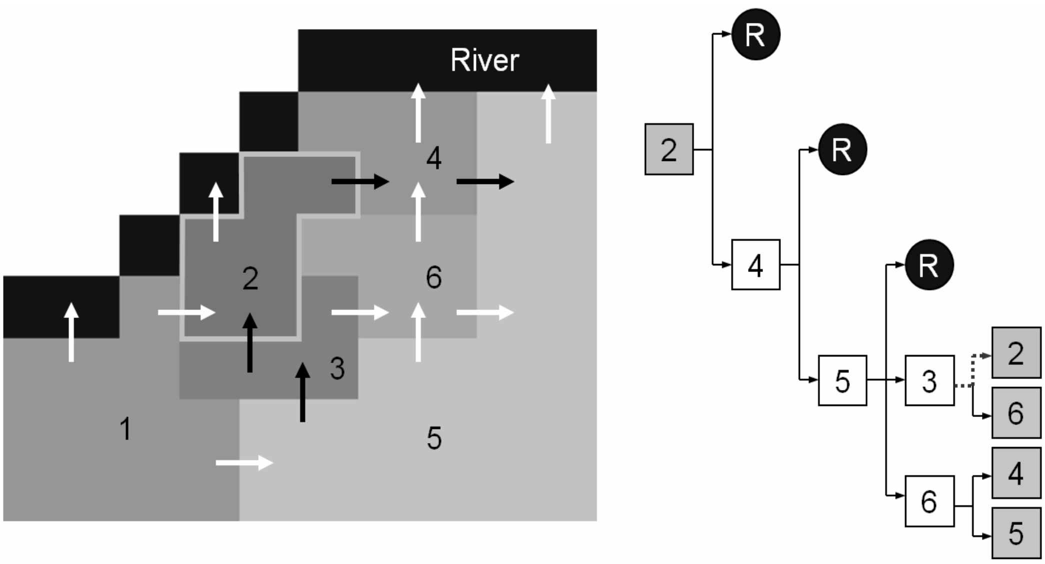

Fig. 2 Identification of circle flows. Left: Part of a catchment area with HRUs and their flow relations. Right: Starting from HRU 2, the directed graph is searched for circle flows. The example shows a circle flow containing the HRUs 4, 5, and 3.

3.3 Dissolving of circle flows

In order to cause the model to transfer water, that is “caught” inside a circle to the catchment outlet it is necessary to dissolve the circle flow. That means to disconnect one of the circle’s water flow relations and to redistribute the emitted water to other entities. This falsifies the overall topology since certain parts of the runoff can no longer be transmitted to the regular modelling entity. To keep this falsification as small as possible, only the flow relation of a circle is interrupted that drains the smallest contributing area.

After an HRU has been identified as part of a circle, the marked flow path is read from the stack and processed recursively until the starting HRU is reached and the contributing area of every water flow relation is determined simultaneously. Then, in order to dissolve the circle, the water flow relation which drains the smallest contributing area is disconnected by setting its value to 0. If possible, the runoff is transmitted to a flow relation of the HRU that is linked with a river segment. If this procedure is used, unnecessary falsification of water balance in other model entities is avoided.

If there is no relation to a river segment, the water is equally distributed to all other flow relations of the HRU. Figure 3 schematically illustrates the procedure for dissolving circle flows.

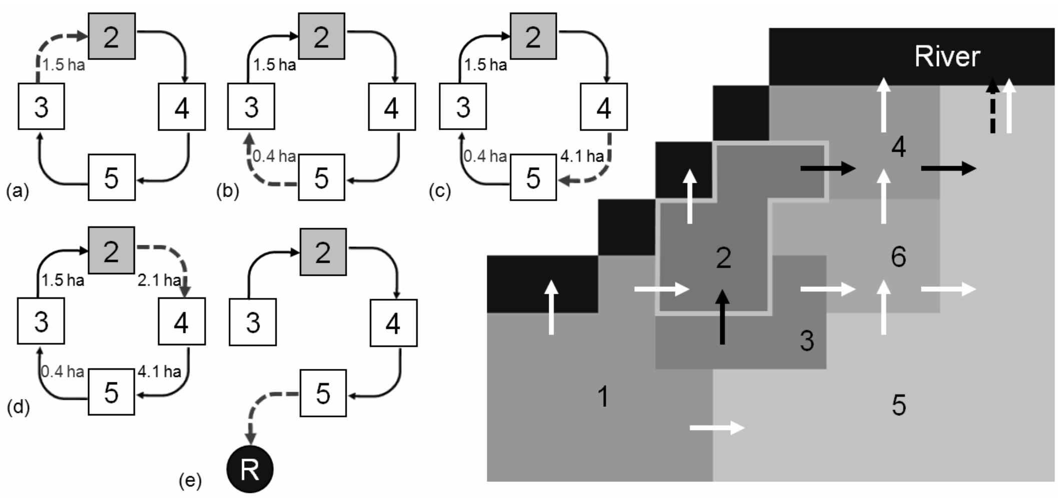

Fig. 3 Dissolving of circle flows. Left side: recursive search for the flow relation with the smallest contributing area (a)–(d); transmission of the runoff parts to another flow relation (e). Right side: processed structure of runoff. Flow relation from HRU 5 to HRU 3 was disconnected and the runoff transferred to the river segment.

3.4 Routing in J2000

The multi-dimensional water transfer between the model entities is realized by implementation of two newly developed J2000 process modules according to whether the soil is considered as a layered or lumped entity. The modules enable the linkage of each model entity with two data arrays that hold the flow relations and their weights. During processing of the topologically sorted HRU list, the data arrays will be read out simultaneous and the water proportion will be transferred to the storages of the receiver entities that follow in the flow direction.

4 STUDY AREA AND BASIS FOR DATA-COLLECTION

The catchment of the Silberleite in Thuringia, Germany, was chosen for a comparative application of the different approaches of topological linkage.

The catchment has an area of 1.4 km^2 that is characterized by altitudes of 450–540 m a.s.m.l. The area is almost entirely covered with managed coniferous forests, only 1.5% is used agriculturally and another 5% is under reforestation. The soil mapping done by Scholten *et al.* (2004) is based on more than 30 soil profiles. Altogether, 15 types of soil, mostly silty to clayey texture, are plotted. The type of landscape of this area is located in the Thuringian Schiefergebirge. A Lower Carboniferous formation consisting of clay slate (shale) and greywacke is shown on the geological survey map (TLUG Jena). The upper layers are heavily jagged for tectonic reasons and promote fast percolation of surface water. Additionally, the bottom of the valley over a large area has been filled with rubble generated through mountain-blasting. This stone mass functions as a flat and very permeable aquifer. For this reason it can be argued that only a part of the runoff of the catchment area can be detected at the outlet level.

A decisive point leading to the selection of this area is the degree of instrumentation. The necessary climate data concerning temperature, radiation, precipitation, wind speed as well as humidity and barometric pressure have been recorded since 1999 at hourly intervals. The discharge data (October 2003–May 2007) calculated from half-hourly water level values by applying the mathematical connection between water level and runoff.

5 HRU-DELINEATION AND MODEL USAGE

On the basis of several hydrologically relevant landscape characteristics, altogether 69 HRUs were delineated for the study area. HRUs are described by Flügel (1996) as heterogeneously structured, distributive and – with regard to process dynamics – aggregated objects in a model. They characterize the spatial variability of hydrological dynamics through disaggregation of the landscape into subareas.

Topological linkage of the model entities has been done by applying both the 1-D (the choice of the proper neighbour was based on the point of highest flow accumulation per HRU) and the multi-dimensional approach, using the procedure described in sections 1 and 3.

For the catchment area of the Silberleite, the extended concept of topology was applied and compared to results achieved with a model using 1-D linkage. In addition to visual comparison, several statistical quality criteria (efficiency, according to Nash & Sutcliffe, 1970) R_{eff} as well as $\log R_{eff}$, coefficient of determination r^2, absolute and relative error of volume) were applied for qualitative evaluation and comparison of model results.

Furthermore hydrograph separation according to Arnold & Allen (1999) was applied to the measured runoff and used for the model calibrations to ensure sufficient cohesion between the inner structure of the model and the physical reality of the ongoing processes.

6 RESULTS

6.1 Topological linkage

When dissolving circles, every change in topology leads to problems when looking at single entities. According to their size and location in the catchment area, single entities within circle relations tend to lose part of their flow relations. Their weights are transferred to other flow relations. This leads to a topological connection shift towards the one-dimensional approach. This case is illustrated for a partial area of the Silberleite catchment in Fig. 4 (left side).

Disconnection of several flow relations at the upper slope reduces the contributing area for direct receivers below. HRU 28, for example, is therefore heavily influenced since it receives no inflow from upslope HRUs. This error propagates through the downstream flow cascades but is weakened by the divergent flowing for the single model entities. The contributing area for HRU 46 is underestimated by only about 15%. This value is once again reduced to about 8% if the HRU's own area is incorporated into its water balance sheet. In contrast to this, the HRU gets totally disconnected from its contributing area if it is connected in a one-dimensional linkage (Fig. 4, right side). From HRU 28 the concentration of runoff exclusively goes in the direction of HRU 34 and afterwards in the direction of HRU 26. Respective flow relations are therefore overestimated to the same degree.

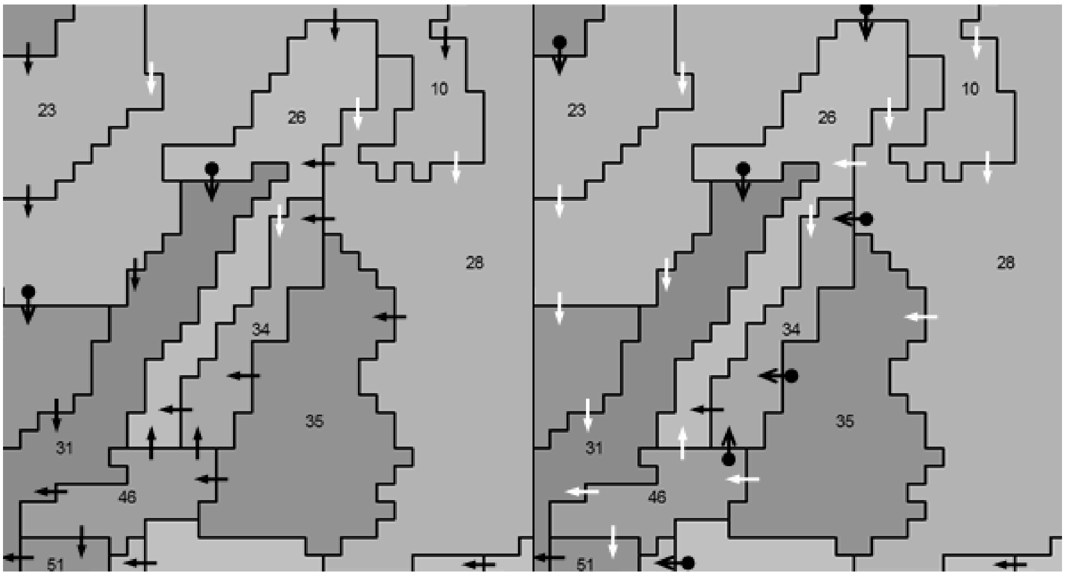

Fig. 4 Left side (multi-dimensional approach): Through dissolving of circle flows, water from the interrupted flow relations ( ) is transferred to other water flow relations of the HRU ( ). Right side (one-dimensional approach): Many flow-relations are not taken into consideration ( ). Contributing areas of others are therefore often overestimated ( ).

6.2 Application of the model

For the period of validation (January–September 2005) a satisfying adaptation of the hydrological dynamics and a coherent relation between single components of runoff was achieved with both models. Considerable differences become visible by analysing the spatial distribution of several runoff components. As can be seen in Fig. 5, 1-D water transfer leads to swift concentration of runoff in the direction of the depth contour lines. For this reason the model simulates much higher runoffs for HRUs that are close to receiving streams than it does for multi-dimensional linkage. On the other hand, inappropriate afflux is assumed for model entities do not reside next to these main 1-D flow paths. Contributing areas that are in part situated in these domains are strongly underestimated which leads, in contrast, to the new approach generating considerably less runoff.

Exemplified by HRU 46, this issue can be explained clearly. Through total disconnection from its contributing area, the total runoff in the 1-D linkage approach is reduced by more than 35% (Fig. 4).

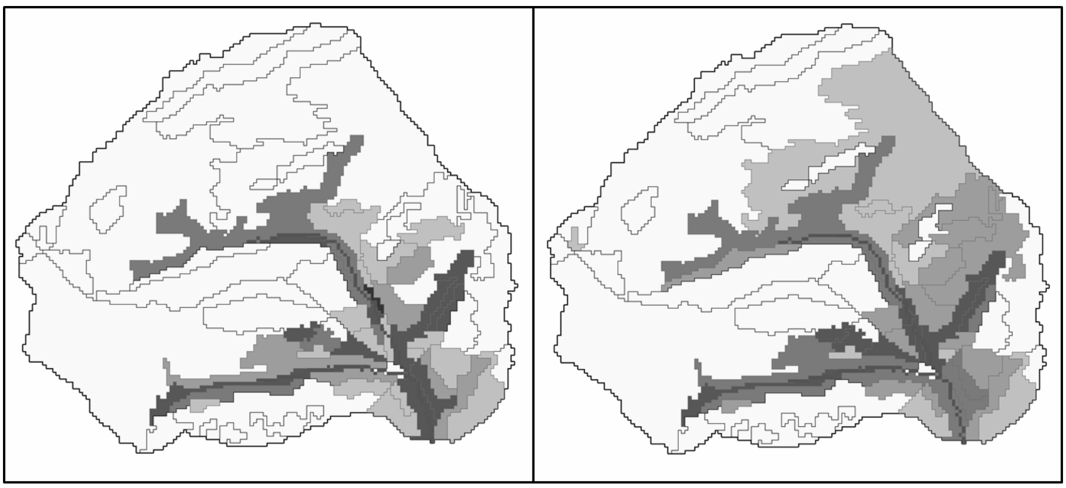

Fig. 5 Spatial distribution of HRU-area weighted predicted runoff for one hydrological year. Left side: one-dimensional approach. Right side: multi dimensional approach.

7 PERSPECTIVES

For water transfer between modelling entities, circle flows are problematic and cause inaccuracies in calculation of contributing areas. Therefore, the current work is focused on the improvement of HRU-delineation in order to avoid circular dependencies in the graph. For that reason, the identification of circle flows and the search for the flow relations with the smallest contributing area should initially be carried out in a GIS so that the sub entities indicating circles can be integrated directly into the HRU-pattern and handled as independent entities. Thereafter, the depth-first search will be started again. This process will be repeated until all circle flows have been eliminated or a threshold for disaggregation of HRUs is reached.

The comparative application of both approaches is realized in additional investigations on the basis of hourly-resolution measurements of five soil moisture stations in the Silberleite catchment, which are available from June 1994. The analysis is carried out by comparison of measured soil moisture data with J2000 modelled soil moisture for each measurement point based on different HRU-disaggregations. Furthermore synthetic surfaces with well-known contribution areas at each point are generated. By disaggregating surfaces in HRUs and their linkage using both approaches, an assessment of the degree of reality of the runoff routing is possible.

Another area of application for the new multi-dimensional routing scheme is the exact assessment of runoff accompanying solute transport processes. With regard to soil erosion in particular, 1-D approaches show functional weaknesses because of the overestimation of rill erosion along the 1-D flow paths by the hydrological model. To enable an exact estimate of the spatial distribution and intensity of soil loss, the development of a suitable J2000 module is planned.

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