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Development of an extended routing scheme in reference to consideration of multi-dimensional flow relations between hydrological model entities

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Abstract Unlike to so called lumped models in which the quantification of several processes results from a statistical relation between system input and system output for the whole catchment, distributed models enable the differentiation of single modelling entities (e.g. Hydrological Response Units – HRU) which can be parameterized and modelled independently. Furthermore spatially distributed hydrological modelling requires a topological linkage of several entities in order to reproduce relevant attenuation and translation processes within the stream but also during the transport of water in form of lateral surface or subsurface flow. Most often such linkage is considered by a one dimensional (1D) approach which links one modelling entity to only one receiver that follows in flow direction. The comparison with actual lateral water movement in catchments show that such a 1D routing scheme is often too simple which can lead to an overestimation of the runoff concentration along the 1D 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 don't receive realistic inflow from their source entities above.

As a catchment-wide consequence the 1D 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 on the spatial distribution of accompanying processes such as spatial variation of soil moisture, soil erosion or solute transport. For example by modelling soil erosion, the one dimensional approaches show functional weaknesses because of the overestimation of rill erosion along the 1D flow paths.

To address the problems outlined above a new two-level 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. On the first level the neighbourhood relations between the model entities are quantified. The area of a HRU which contributes to the runoff to one of its neighbours is compared to the overall contribution area of the same HRU. As a result a fraction of the entire runoff can be assigned to every flow relation. In a second step, an exact analysis of the flow cascades is conducted to identify so-called circle flows, in which the runoff of a HRU flows back to the same HRU. Throughout the model run, the runoff of the HRUs involved in a circle flow is not routed to catchments outlet. The improved routing method introduces a new approach for the elimination of circle flows by modifying certain flow relations without altering the whole topology abundantly.

This extended routing scheme was implemented in the hydrological modelling system J2000 and was used for the simulation of the hydrological processes of a number of meso-scaled catchments in Thuringia, Germany.

The paper will present the most important facts of the extended routing scheme, the first simulation results along with the comparison of those obtained with the 1D linkage and will highlight the impacts on the hydrological process dynamics.

Keywords *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, the elevation data of the *Shuttle Radar Topography Mission (SRTM)* most often is the only spatial data available on a high resolution. To satisfy the demand to include these catchments in planning of water management it is essential to tap the full potential of this data source and to understand the impact of relief on researched hydrological processes completely. 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 presented work 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 approach may lead to imprecise result when calculating the contributing areas. On the one hand, the contributing areas along the 1D 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 1D flow paths. This has a strong impact on the processes which are directly related to the contributing area, such as the spatial distribution of the soil humidity, the value of soil erosion, and the mass transport.

2 RESEARCH OBJECTIVES

The demands for an extended approach for the derivation of hydrological topologies can be summarized as follows: A linkage is aspired 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 should 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 (KRAUSE 2001). Then, the model is initialized and the hierarchy of HRUs within the flow cascade, the so called topological sortation, 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 lies downward 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 precondition 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 which represents the weight of the overall runoff of an HRU (node). The derivation of flow relations as well as the calculation of their weights is carried out in a GIS. Based on an analysis of the flow direction grid the grid cells from the HRU sample are extracted, which 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 the 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).

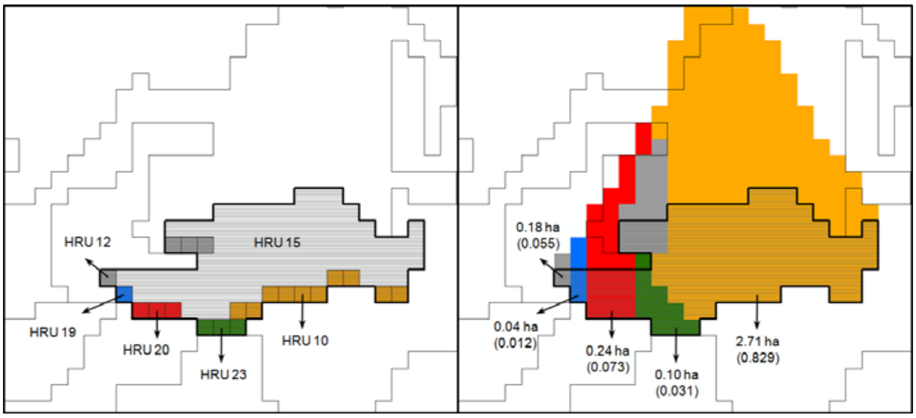

Fig. 1: Derivation of more dimensional flow relations. Left side: Extraction of all grid cells which drain to another HRU. Right side: Calculation of the weight of the flow relations from the specific catchment areas.

The specific catchment areas are suitable for the calculation of weights, because it incorporates the position of the flow relations within a runoff cascade and therefore reproduce 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 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.

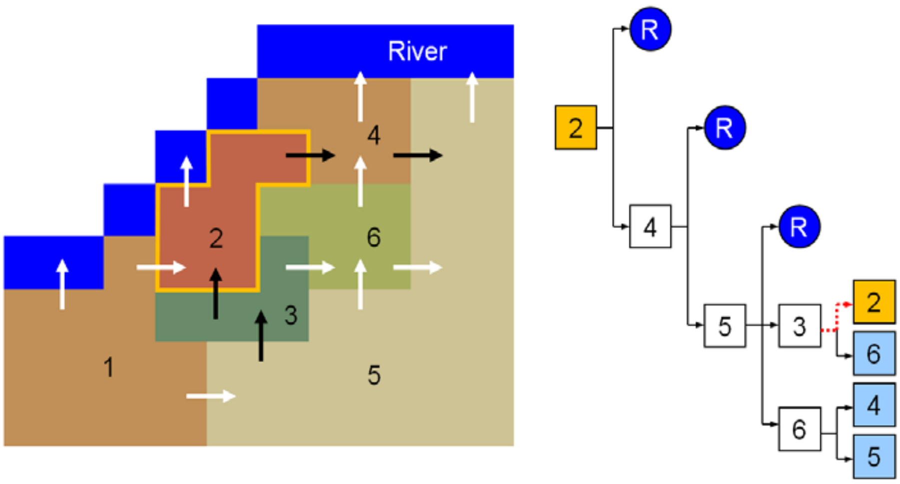

Fig. 2: Identification of circle flows. Left side: Part of a catchment area with HRUs and their flow relations. Right side: Starting from HRU 2 the directed graph is searched for circle flows. The example shows a circle flow containing the HRUs 4, 5, and 3.

For the identification of circle flows it is necessary to make the flow path of the water through the catchment traceable. That's why the vertices-edge-structure is analyzed 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 (TURAU 2004).

Starting from each HRU the neighbours are searched to which a flow relation exists. 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 a 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 algorithm returns to the last intersection (backtracking) and another path is searched until one of the aforementioned abort criterions is the case. The search is continued until no more vertices exist, that are reachable from the starting HRU.

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

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 runoff cannot be transmitted to the regular modelling entity any longer. To keep this falsification as small as possible, only the flow relation of a circle is interrupted that drains the smallest contributing area.

After a HRU has been identified as part of a circle, the marked flow path is read from the stack and recursively processed 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. The parts of runoff are at best 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. Fig. 3 schematically illustrates the procedure for dissolving circle flows.

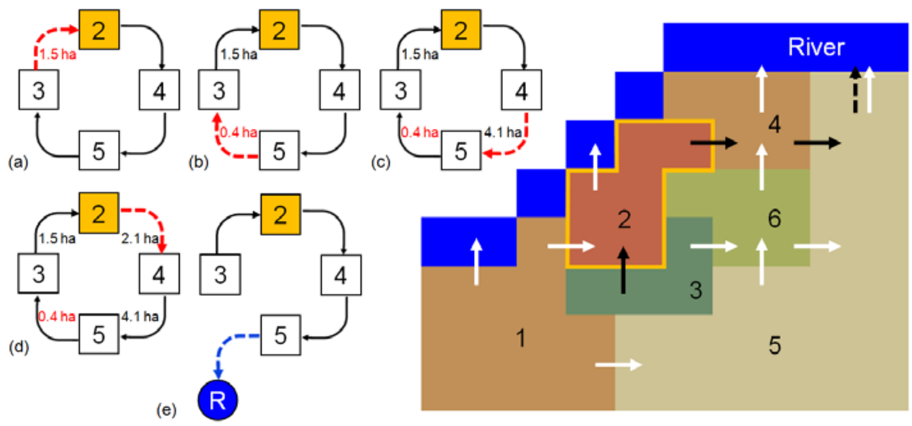

Fig. 3: Dissolving of circle flows. Left side: recursive search for the flow relation with the smallest contributing area (a-d). Transmission of the runoff parts to another flow relation (e). Right side: processed structure of runoff.

A flow relation can only be disconnected when other flow relations are available which ensure the runoff from the HRU because otherwise a sink would be generated where the water is trapped in. In this case the flow relation with a contributing area next in size is selected.

3.4. Routing in J2000

The multi-dimensional water transfer between the model entities is realized by the implementation of two newly developed J2000 process modules according, depending on if 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 the topological sorted HRU-list the data arrays will be read out simultaneous and the water proportion will be transferred to the storages of receiver entities that follow in flow direction.

4. STUDY AREA

The catchment of Lossa in Thuringia, Germany, was chosen for a compared application of the different approaches of topological linkage. This means we are dealing with a part of the Lossa catchment (233 km2), an area of 26.29 km2 that is characterized by altitudes between 210 and 356 meters above sea level. The catchment is located in natural landscape unit, the Central Thuringian Farmland. 63% is agriculturally used area, 15% is covered by coniferous forest, 10 % is covered by scrubland, 5% is covered by mixed forest, 5% is covered by greenland and the rest are urban areas. In this area the mean annual precipitation is between 500 and 600 mm and the mean annual temperature is 9 °C. The geological underground consists of layers from Under Keuper and Middle Keuper. In the part of Lossa catchment are 11 different soil types. The soils are mostly sandy to loamy cambisols.

5. HRU-DELINEATION AND MODEL USAGE

HRUs are described by FLÜGEL (1996) as heterogeneously structured, distributive and – regarding to process dynamics – aggregated objects of a model. They characterize spatial variability of hydrological dynamics through disaggregation of the landscape in subareas. On the basis of several hydrologically relevant landscape characteristics, altogether 2137 HRUs were delineated for the part of Lossa catchment.
Topological linkage of the model entities has been done by applying both the one-dimensional (the choice of the proper neighbour was based on the point of highest flow accumulation per HRU) and the multi-dimensional approaches, using the procedure described in Sections 1 and 3. In addition the J2000 model results are used to visual comparison, several statistical quality criteria (efficiency, according to Nash & Sutcliffe (1970), coefficient of determination, absolute and relative error of volume) were applied for qualitative evaluation and comparison.
Furthermore hydrograph separation according to ARNOLD & ALLEN (1999) was applied to the measured runoff and applied for model calibrations, to ensure sufficient cohesion between inner structure of the model and 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 Lossa catchment in Fig. 4 (left side).

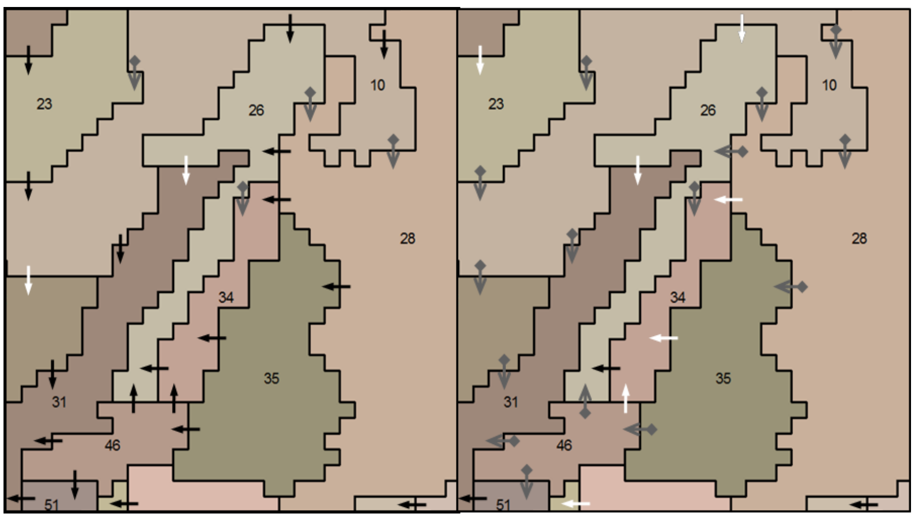

Fig. 4: Left side (multi-dimensional approach): By dissolving circle flows, water from the interrupted flow relations ( ) is transferred to other water flow relations of the HRU ( ). Right side (one-dimensional approach): Many flow-relations are not taken into consideration ( ). Contributing areas of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

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 at a degree of just 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 concentration of runoff exclusively goes into the direction of HRU 34 and afterwards into the direction of HRU 26. Respective flow relations are therefore overestimated to the same degree.

6.2. Application of the Model

With the hydrological modelling system J2000 and the integrated module for sediment yield / soil loss prediction, the different linkage approaches were analyzed. The calculation of sediment yield (SY in tons) using the Modified Universal Soil Loss Equation (MUSLE) with a dynamic factor, the runoff factor calculated in J2000. The MUSLE follows the structure of the Universal Soil Loss Equation (USLE), with the exception that rainfall factor R replaced with the runoff factor. The equation calculates sediment yield / soil loss from a rainfall event for each HRU. The structure of used MUSLE is:

$SY = R * K * L * S * C * P * ROKF$ where $R = 11.8 (Q * q_p * A_{HRU})^{0.56}$

therefore

$$SY = 11.8 (Q * q_p * A_{HRU})^{0.56} * K * L * S * C * P * ROKF.$$

with the factors:

Q = volume of runoff in mm	S = slope gradient factor
q_p = peak flow rate in m^3 per second	C = cover and management factor
K = soil erodibility factor	P = support practice factor
L = slope-length factor	ROKF = coarse fragment content factor

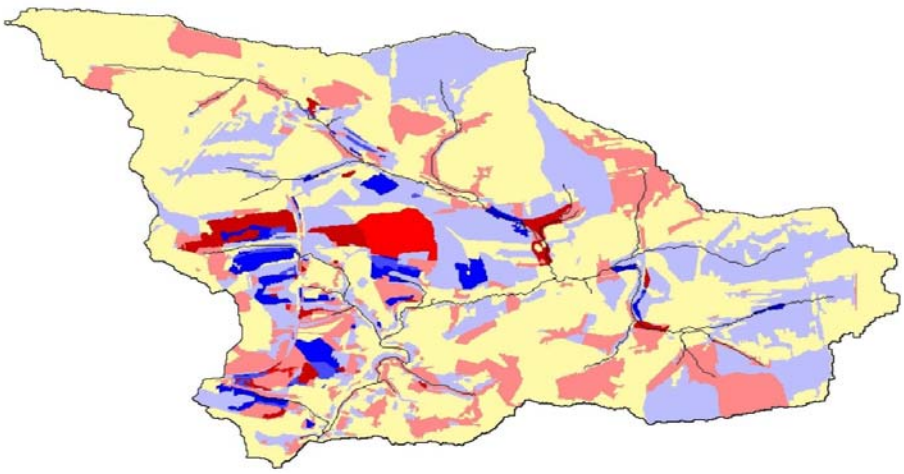

Fig. 5: Difference-map, one-dimensional approach minus multi-dimensional approach by calculation of sediment yield, using J2000 with MUSLE-module
Blue: multi-dimensional approach has more predicted sediment yield
Yellow: no differences or no sediment yield
Red: one-dimensional approach has more predicted sediment yield

For the period of validation (January 1999 to December 2000) a satisfying adaptation of hydrological dynamics and a coherent relation between single components of soil loss was achieved with both models. Considerable differences become visible by analysing the spatial distribution of several soil loss components. In fig. 5, one-dimensional water transfer leads to swift concentration of runoff into the direction of depth contour lines. This is illustrated by the red coloured HRUs. For this reason the model simulates much higher runoff values and more soil loss for HRUs that are close to receiving streams (streams in Fig. 5 as black lines illustrated). Multi-dimensional water transfer, this is illustrated by the blue coloured HRUs, generates less runoff into the direction of depth contour lines. And relocated runoff water flows in more HRUs as when using the one-dimensional approach. By applying the multi-dimensional approach the model result are closer to reality, because runoff in reality flows multi-dimensional!

7. PERSPECTIVES

For water transfer between modelling entities circle flows are a problematic issue and their dissolution is the reason for inaccuracies in the calculation of contributing areas. Therefore, the current work is focused on finding a way to dissolve identified circle flows not by disconnection of a certain flow relation. Instead the sub entities which are associated with these flow relations should be disaggregated from their HRU and used as independent entities for routing processes afterwards. However, the membership to the original HRU is endured. The J2000 process modules will be modified in a way routing processes are realized based on the new sub entities whereas the calculation of runoff on HRU basis is retained unchanged. After each model time step the simulated water balance quantities of all sub entities corresponding to the same HRU will be aggregated. Furthermore, an area of application for the new multi-dimensional routing scheme is the exact assessment of runoff accompanying processes of solute transport. To enable an exact estimate about the spatial distribution and intensity of solute transports the contemporary development of suitable J2000 module is planned.

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