Extraction of process-based topographic model units using SRTM elevation data for Prediction in Ungauged Basins (PUB) in different landscapes

Pfennig, B. and M. Wolf

Department of Geoinformatics, Geohydrology and Modelling, Friedrich-Schiller University Jena, Germany

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EXTENDED ABSTRACT

The concept of this research is justified to the integration of landscape components for hydrological modelling within distributed models. Distributed models are based on homogeneous entities which are delineated using landscape parameters such as topography, land use, soil, and geology. In *ungauged basins* most of these required data are only available on a coarse spatial resolution. In order to by-pass this gap the globally and freely available data from the *Shuttle Radar Topography Mission* (SRTM) were used to obtain model entities on an adequate resolution of 30m and 90m. The research relates to two research hypotheses that focus on the integration of landscape components in hydrological modelling for the application in the program *Prediction of Ungauged Basins* (PUB) of the *International Association of Hydrological Sciences* (IAHS). The method relies on the assumption of a strong, process-driven feedback between the topography and further landscape components as well as runoff dynamics which can be quantified using geoinformation techniques. It is expected that the water balance of catchments with insufficient hydrometric infrastructure and data availability can be estimated using SRTM-based delineations of process-oriented model entities. Entities represent *response units* (RU) which were implemented in distributive hydrological models.

Overall goal was to investigate the potential of SRTM-data for delineation of process relevant response units over various scales. An optimisation of the elevation data was therefore required to improve the SRTM-relief for hydrological applications. Improvements are necessary to embrace drawbacks in the interferometric radar data. Those effects result from geometric and radiometric errors as well as interaction properties of electro-magnetic waves with the surface. Resulting limitations in the SRTM-data could be diminished using several GIS procedures and new algorithms for void filling, vegetation reduction, hydrological oriented filter combinations and stream burning. Amongst others preparations a new developed sink fill method was implemented with the name LaSA (Landscape based Sink Algorithm). Main problems were vegetation offsets and narrow valleys that caused embarrassments at InSAR-DEMs in terms of ‘digital dams’ and hydrological sinks. Standard algorithm to fill sinks can cause strong variations of the DEM-topography. The objective of LaSA is a minimisation of the interferences in DEM surfaces. Elimination of sinks should be realized by a landscape-based optimum between filling sinks and carving of flow paths in flow barriers.

In result of the DEM-preparation, hydrological corrected SRTM data were available to establish a ruled-based framework for RU-delineation. Numerous topographic indices were applied on these data whereas the index selection was oriented on different relief driven processes. Taking into account the scale problem several indices such as *Topographic Wetness Index*, *Stream Power Index* were investigated in three subcatchments of the river *Saale* (Germany) with different landscape characteristics and thresholds for their classification were determined. The resulting datasets were analysed by the Cluster Analysis IVHG. This approach combines areas with small displacements in the multivariate space only under the constraint of an immediate neighbourhood. Under consideration of method transferability and scale a landscape dependent roughness index was integrated into data preparation. That led to a balanced representation of different landscape types. In order to determine the best level of generalisation significant changes of distance vectors were analysed. Finally, different patterns of process driven RU combining various topographic indices were delineated for the three mesoscale-catchments within different landscape types. These RU-sets were used as input entities in the hydrological model J2000. The analysis of significance of the different landscape components to estimate runoff dynamics will define the potential of this approach for the use in *ungauged basins*.

1. INTRODUCTION

In many catchments a lack of data for discharge, precipitation and groundwater exist due to insufficient hydrometric infrastructure. The immediate demand to involve these river catchments in sustainable planning of water balance determined the goals of the research program '*Prediction in Ungauged Basins*' by the *International Association of Hydrological Sciences* (IAHS). Until now no relief information are existent for those *ungauged basins* or are only present in an inadequate resolution. Around 90 percent of all global catchments are *ungauged basins.* Topography performs, however, an essential impact on hydrological and geomorphologic processes in landscape. Since the *Shuttle Radar Topography Mission (SRTM)* launched in February 2000 there has been a homogeneous digital elevation dataset with a nearly global coverage available. These data represent the GIS-database for the regionalisation and quantification of the catchment characteristics based on *Hydrological Response Units* (HRU) for this research. *Response Units* are topological connected, distributive model entities for surface area specific water and mass transport modelling. The process oriented regionalisation concept defines HRUs as areas of homogeneous topographic and physiographic environment and therefore hydrological system response (Flügel 1996).

Based on that, following key question can be posted for this work: *„Is it possible to get a realistic analysis and modelling of runoff dynamic on a river catchment in spite of insufficient hydro-meteorological data base and a lack of other disposable landscape components?"* Because the required data for developing countries are often not available on desired spatial resolution and quality we want to answer this question by a geomorphologic oriented HRU approach. For this intension the globally available and free SRTM-DEMs shall be used.

2. OBJECTIVES

Main objective of this work is the investigation of the scale comprehensive applicability of SRTM-data for delineating process relevant response units (RU) over various scales. In addition to the SRTM3 (90m) product the X-SAR SRTM data (30m) were used. The use of radar elevation products like SRTM-data occur a preparation of elevation data for hydrological optimisation. Quality checked, error corrected and hydrologically prepared elevation data are needed to realise a scale oriented comparative relief analysis. Those derivations have to be integrated in an automated GIS-tool for user driven HRU-delineation under comprehension of further landscape components.

The main goal in HRU-delineation is the development of a geomorphological based method. The currently used HRU concept implements the relief parameter slope and aspect for the intersection with other landscape components. But there are deficiencies in regard to hydrological process orientation. Slope alone is not able to examine processes of quickening or divergence and convergence of water flow respectively. The spatial distribution of soil wetness can also not be considered. Therefore the aim of the research is to integrate indices with more significance for runoff processes to increase the process delivery. Another problem consists in structural deficiencies of the current GIS-approach. The pre-classification of input data for HRU derivation has to occur after fixed schemata. It is though not possible to determinate sharp borders for the appearance of investigated hydrologic processes. In addition the potential of the indices to characterise the hydrological processes is highly scale dependent. To solve the problems and overcome the disadvantages a cluster based HRU delineation was designed for this research.

3. METHOD

The work was done by the following approach. Initially the quality of the SRTM data was assessed and the data was prepared for hydrological issues. Subsequently the corrected data were integrated to realise a scale oriented comparative relief analysis. The derived topographic indices were used in a process oriented HRU sub-areas derivation using further landscape components. The delineated HRUs were joined topologically for runoff routing and served as model entities for a comparative river catchment modelling with the distributive hydrological model J2000 (Krause and Flügel 2001) in investigation areas of different landscape characteristics. Three subcatchments of the river *Saale* were selected (*Upper Ilm, Roda, Helbe*) for development of the methodology and four sub-catchments in *South Africa* (*Mooi, Olifants, Mkomazi, Sandspurit*) to test the transferability of the methodology. Further test sites in the Brahmaputra catchment are intended. By means of analysis the significance of the different landscape components to estimate runoff dynamics the potential of this approach for the use in *ungauged basins will be defined.*

3.1 SRTM data preparation

SRTM is an interferometric SAR product that underlies specific characteristics of generation technique. These radar specific effects restrict the handling of river catchment related analyses and the derivation of hydrological indices. The effects are caused by geometric and radiometric errors as well as interactions between electro-magnetic waves and the surface. The limitations required specific surface area corrections to prepare the SRTM elevation model for hydrological applications in issues of regionalisation and catchment modelling. For that purpose criteria have been developed to optimise the applicability and its implementation in a geoinformatic-toolset for user driven error elimination of SRTM3 and SRTM/X-SAR data. The SRTM corrections included the elimination of areas with poor coherence, interpolation of data voids, filling of larger gaps with ancillary data and hydrological adapted filter combinations. The hydrological conditioning was concentrated on water body corrections, the reduction of vegetation offsets, which are included in SAR elevation data and the removal of flow barriers and flow depressions to afford the runoff routing. Finally hydrological prepared and optimised SRTM elevation data were provided.

The SRTM quality assessment results were compared with a photogrammetrically derived Digital Terrain Model (DTM) of the Thuringian Survey Agency and ERS Tandem Mission data (C-Band). The analysis were realised in test sites comprising difference images between several DEMs. Furthermore statistical analysis and quality estimations as well as the derivation of secondary DEM products like slope, aspect, curvature, catchment area, river density, flow direction, flow accumulation and transport capacity were taken into account. These parameters were used as spatial input data for the distributed hydrological model J2000.

3.2 Landscape based sink algorithm (LaSA)

The availability of high resolution elevation data has antiquated the assumption that all sinks are data artefacts (Linsay and Creed 2006). It is necessary to distinguish several causes and kinds of sinks. Closed depressions are not always determined by elevation underestimation of cells inside the sink. They can equally well produced by elevation overestimation of cells around the sink outlet (Martz and Garbrecht 1999). Floodplain forest builds up flow barriers which causes depressions in the runoff model because the real flow path is barred through the vegetation. Besides the vegetation there are numerous other causes for sinks. Especially flatland areas lead to complications because inherently marginal elevation offsets can cause large-area depressions. Also ‘digital dams’ occurs in narrow valleys which can not be dissolved geometrically by the raster resolution. At such narrows the DEM resolution is too coarse to represent the valley bottom. Therefore the pixel contains backscatter information from the bordering hillsides and obtains a considerably higher elevation value. Anthropogenic buildings like bridges or dams can build up undesirable flow barriers as well, because they were captured by the radar beam too.

The possibilities of an adequate correction of elevation offsets caused by vegetation are very limited. A correction is essentially depending on the quality of available forest inventory data but is also related to numerous factors, which are difficult to quantify, like tree morphology, tree canopy, storm damages, mixed forest and many others. Despite these difficulties an accurate computation of runoff paths and elimination of flow barriers is essential. Standard methods to fill the resulting runoff sinks, like the approach after Jenson and Domingue (1988), lift the pixel values on the elevation level of the sink outlet. This approach often results in large surface interventions in DEM topography. Because all topographic information inside the sink get lost and were not considered in derivation of flow paths. Other methods assume that the flow barrier itself is the problem. So the algorithms regard the elevation values at the sink outlet as to high. Hence the flow path will be burned in the flow barrier. Thereby it could happen that in the DEM depth canals will be created. In the worst case this canals carry forward for long distances.

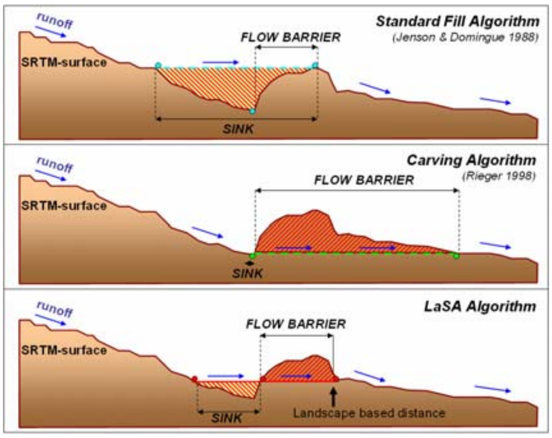

Figure 1. Comparison between different sink fill techniques: Standard fill algorithm (Jenson and Domingue 1988), Carving algorithm (Rieger 1998) and Landscape based sink algorithm

To minimise the volume and area of modifications by sink filling the *Landscape based Sink Algorithm* (LaSA) was designed (figure 1). The objective is the minimisation of interferences in DEM surfaces by the sink filling process. Elimination of sinks should be realized by a landscape-based optimum between filling sinks and carving of flow paths. Thresholds based on relief characteristics support the selection of an optimal solution. Depending on depth and extent of sinks the LaSA algorithm decides how to prepare the sink: (I) filling the sinks, (II) carving flow barriers or (III) partially filling of sinks and carving in landscape based distances and relations.

The routine works in the way visualised in the diagram in figure 2. A depression will be filled by the standard method if the extent of the sink is very small. The flow path will be burned in the 'digital dam' if the sink is very large in area but small in depth. Is the depression in depth and area very large we assume that the sink has got a naturally origin and will be retained unchanged. In all other cases the depression will be partial filled and the flow path burned in the barrier. Thereby the ratio between filling and burning is dependent on the ratio between depth and area of the sink. The interval borders for the different routines were defined by landscape based thresholds based on surface roughness.

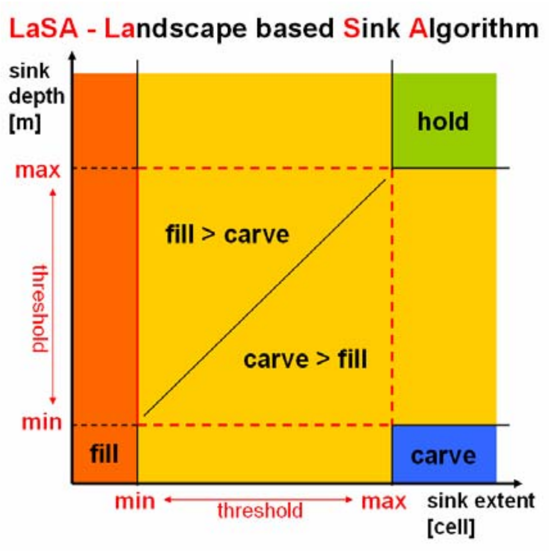

Figure 2. Sink fill routines in the LaSA algorithm

On the base of the prepared SRTM elevation data the relief parameters were derived within a relief analysis. These indices were included into a relief based process area derivation to derive hydrological homogenous units (HRU).

3.3 Delineation of relief based process entities

Parameter selection

The interdigitation of hydrological processes is controlled by the three-dimensional and unique landscape properties of each catchment (Flügel, 1996). Hereby, topography is the most important factor for influencing other landscape components such as evolution of the soil catena or the forming of land cover patterns. In the current applied approach for the delineation of hydrological response units slope is the most significant relief parameter because it affects surface runoff and interflow processes as well as the degree of soil erosion. However, there is no relation to the relief curvature an important factor for spatial distribution of erosion or accumulation zones. Additionally, a linkage to the upslope contribution area that is essential for the development of saturation areas is lacking.

Hence the developed approach integrates different relief parameters, such as Topographic Wetness Index (after Böhner et al. 2002), Mass Balance Index and Annual Solar Radiation Index (McCune & Dylan 2002) in an extended criteria catalogue for the HRU delineation. In addition, the selection was orientated on the scaling ability of the parameters and to the possibility of extracting major hydrological variables by using well-fitted transfer functions respectively. So, the developed methodology can be applied to regions in which the SRTM3 elevation model is the only topography data source.

Data preparation

The delineation of homogenous model entities was realized by a complete linkage cluster analysis with the program IVHG. Friedrich (1996) proposed this approach which only aggregates basic units with the smallest Euclidean displacement in the multivariate space to a new entity under the requirement that a spatial neighbourhood in the data matrix exists. So, the demarcation of local relief units can be optimized. Initially a detailed data preparation is essential for the cluster analysis. In areas with gentle relief the investigated parameters show only a small value range whereby an exact classification of different relief forms will be difficult. To overcome this problem, Friedrich (1996) used the following simple equation: $f(P) = P / (|P| + T)$. Thereby large distances in the multivariate space will be compressed whereas small distances will be stretched. The constant T determines, hereby, the intensity of the data manipulation and will be transformed in the range from 0,5 and -0,5 of the new scale. This means that the parameter values P laying between –T and T will be assigned to the half value range. Therefore, T should be selected according to the local relief characteristics. A transfer to other landscapes without adequate adaptation is problematic so the methodology had been modified. The transformation constant T was changed to the median of the particular relief parameter in a user defined window (420 m × 420 m). The median of all relief parameters highly correlates with the local relief amplitude calculated as range between highest and lowest elevation in the same window and used as a representative roughness parameter for the respective landscape. Also, the median is very robust to outlier values. A response of T to relief changes only occurs if more than half of raster values in the defined window are reflecting the same trend. According to this, a moving local adaptation of T depending on landscape takes place. In result, a well balanced differentiation of landform units will be achieved. This differentiation is limited to regions classified as process relevant areas by existing process knowledge. If the median deserts a user defined range the adaptation of T is determined using an exponential function. In these relief areas the Euclidean displacements become very small between the different units whereby only significant relief forms will be differentiated.

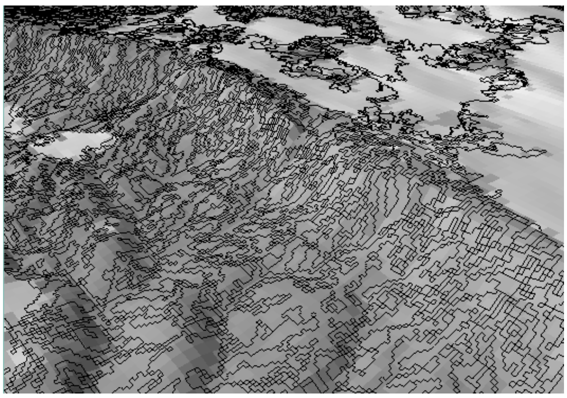

Figure 3. 3D-perspective of the tangential curvature segmentation in the north western part of the Helbe catchment

The user has the opportunity to control the width of the transition range of process relevant and non relevant areas by varying the function's slope. A smaller slope value causes a more gently and smooth transition band. Thus, zones with fuzzy hydrological process dominance can be better delineated. The determination of the process relevant value range and its function's slope need fundamental knowledge of the investigated processes with the goal of exact deviation of process relevant and non relevant areas.

Figure 3 shows the derived homogenous areas for tangential curvature in the north western part of the Helbe catchment. In order to take into account erosion and accumulation processes of soil material the value range of this parameter was set to radii between 100 m and 3000 m according to Friedrich (1996) whereas larger radii are not important. Under this perspective two adequate ranges for the local median were derived and treated differently as described above. In more gently relief with large radii (light coloured) a minimization of the Euclidean displacements was reached by using an exponential function. Hence, in the dark coloured, rougher areas are considerable finer and more accurate degree of segmentation was achieved.

Choosing of halting criterion

The generalisation level was based on the following requirements:
(i) to achieve the lowest number of process-based landscape entities
(ii) the entities should have a maximum of internal homogeneity
(iii) further aggregation from a hydrological point of view is not reasonable

During clustering the main focus was to delineate heterogeneity saltus of the Euclidean displacements. These are cyclic effects caused due to transitions in scale and depend on the respective landscape. The main reason is the merging of homogeneous entities with adjacent, relative dissimilar geomorphographic units. Afterwards, there are phases in which the rising of the distance vector is diminishing again. According to such behaviour, the abruption of the cluster analysis should be realized before such a heterogeneity saltus occurs. The best halting criterion combines a high degree of generalisation and an exact relationship of the investigated processes to the delineated entities. In the case that landscape objects with different process proportions have been merged a lower degree of generalisation has to be applied. Finally, the averaged characteristics of each individual entity have to be assigned by analysing the cluster centroids.

The validation of different RU-delineations was carried out classifying several landscape forms into more general landscape types using an iterative cluster analysis. Afterwards, these classes were analysed statistically according to the value ranges of integrated relief parameters and to the information loss due to the generalisation process. Also, representative RUs delineated with different generalisation degrees will be validated directly in the test catchments by distinction of these in the field and analysing their internal process dynamics

Topological linkage

For the simulation of runoff relevant damping and delay processes along the stream as well as the spatial consideration of lateral flow between adjacent entities the topological linkage of those is necessary. Staudenrausch (2001) realized this linkage using the points of the highest flow accumulation. The methodological deficit of that approach is the linkage of a RU with only one underlying entity whereas runoff can be distributed divergent to several underlying entities. A theoretical problem solving would be the segmentation into several flow paths by overlaying the entities with their delineated drainage areas.

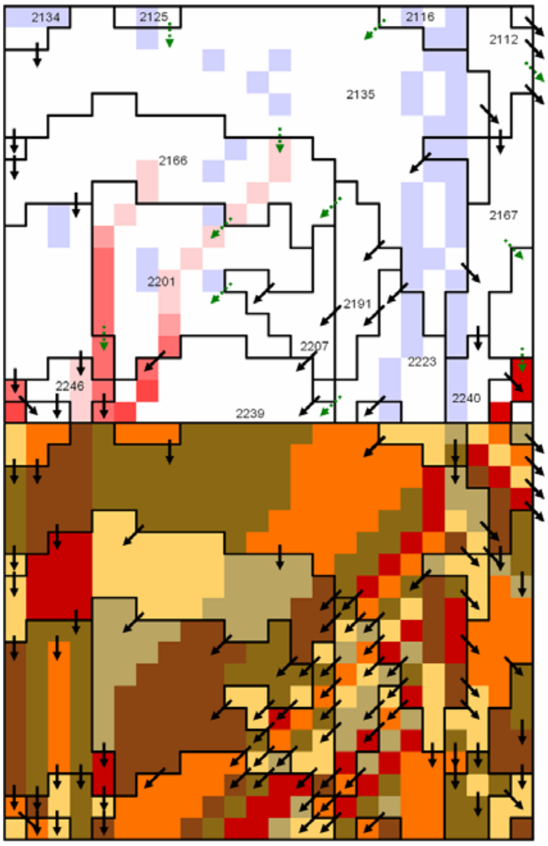

Figure 4. Above: Topologic linkage using the points of highest flow accumulation (green dashed arrows). The other flow relation (black arrows) are not considered. Below: Concept of disaggregated flow paths with 1:1-relations between the sub-entities of homogenous RUs

The new generated sub-entities are characterized by a clear flow relation to each other and accordingly, drain to only one underlying entity. However, the extensive fragmentation of homogenous RUs is very problematic and disagrees with the basic idea of the HRU-approach. According to Flügel (1996) the process dynamics between adjacent entities are assessed as more significant as the negligible, internal process variations of one entity. Furthermore, the large number of entities with similar characteristics tends to a redundant calculation effort in the modelling process. In figure 4 both described concepts are shown.

The new approach integrates the advantages of both methodologies. Following the disaggregated flow paths (see above), a comprehensive analysis of every flow cascade has been carried out. The calculated flow cascade of every sub-entity is checked against hits a sub-entity of the same RU. The simulated runoff of entities involved in this so-called circle flow is not routed to the outlet. This leads to backwater effects with the consequence of an erroneous water balance. Circle flows can be dissolved by deletion the flow relationship between the circle-initiating sub-entity and their underlying sub-entity.

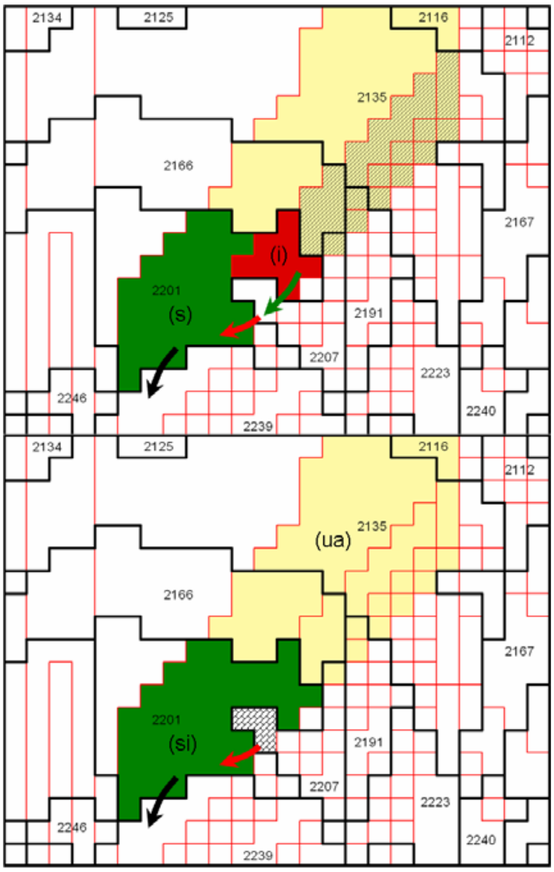

Figure 5. Dissolving a circle flow. Above: Circle-initiating (i) and circle-solving (s) sub-entity; Below: Merged into a spatial unit (si) with common upslope area (ua); the flow relation between the circle-initiating and enclosed sub-entity is interrupted.

Afterwards circle-initiating and circle-solving sub-entity will be merged to a spatial unit with a uniform drainage direction. This drainage direction is taken from the circle-solving entity whereas enclosed entities forms an independent flow cascade draining into the new generated entity. Figure 5 shows the dissolving procedure.

Finally, all sub-entities of a RU draining into the same underlying RU will be merged. The character of the runoff relation between two adjacent RUs can be quantified by calculating the topographic wetness index (TWI) from average upslope area and their average slope. On the one hand, a significant relationship between TWI and the groundwater level exists and therefore to the process of saturation area generation. On the other hand, upslope contributing area is an important indicator for groundwater flow quantification. By implementation of the approach in the used modelling system J2000 a more realistic reproduction of lateral flows between the delineated entities is feasible.

4. CONCLUSION AND OUTLOOK

The corrected and optimized SRTM data produced a better delineated stream network which has been validated with the digitised streams from the topographic map TK 1:25000. Thus, large errors in the delineated surface runoff were corrected and hydrological optimized, physically based relief parameters were provided. The parameters were prepared according to the heterogeneity of landscape using the introduced methodology. Afterwards, the relief parameters were integrated into the cluster analysis for a better assignment from investigated processes of delineated homogeneous entities. This procedure allows a well balanced delineation of process relevant surface objects and their classification independently of the respective landscape. The used halting criterion ensures the concomitance of a high generalisation degree and a maximal possible internal heterogeneity of the entities. Furthermore, a new approach for topological linkage of adjacent entities was introduced which allows to derivate multiple flow paths. RU's can be connected with more than one of their underlying entities or river segments (1:n-relations). The process-oriented character of the based HRU-approach and its simplicity endures. Overall, after implementation in J2000 a more realistic simulation of lateral flow processes between the delineated entities will be achieved.

The global available SRTM data provide the possibility to automate GIS-based algorithms for the derivation of model entities. The development of such algorithms makes the process of the HRU derivation more transparent and repeatable. Derivations of different studies and similar issues are allowed to be compared. This is a main issue of the PUB initiative of the IAHS. Case studies in different climates show the capability of the analysis of landscape components to explain the hydrological dynamic within the water balance. Focused on the reduction of the feasible parameter range for a priori parameter estimation as well as an improvement of a parameter transference function these algorithms will help to represent hydrological processes with poorly calibrated models. Finally this approach will support an assessment of accuracy of model results for *ungauged basins*.

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