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Delineation of topographic process entities using SRTM for hydrological modelling

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Abstract: The concept of distributed hydrological models is based on the integration of landscape components to delineate distributed process entities. These Hydrological Response Units (HRU) are topologically connected model entities and represent areas of homogeneous topographic and physiographic environment and therewith the hydrological system response. The HRU regionalisation concept is realised by the intersection of landscape parameters such as topography, land use, soils and geology. In many river catchments of the world most of these required data are only available on a coarse spatial resolution or poor quality. Furthermore, there is often a lack of data for discharge and precipitation. The demand for involving these catchments in planning of water management has determined the goals of the research program *Prediction in Ungauged Basins* (PUB) by the *International Association of Hydrological Sciences* (IAHS). The availability of new remote sensing products provides the opportunity to by-pass these data gaps and offers a GIS-database for regionalisation of river catchments based on HRUs.

Topography is one of the most important factors for runoff and it is influencing the evolution of other landscape components such as soil catena or land cover patterns. The assumption of a strong, process-driven feedback between the topography and further landscape components as well as runoff dynamics lead us to a modified delineation of process entities by a topographic oriented HRU approach on the base of the globally and freely available SRTM elevation data. The methodology is based on the expectation that the water balance of watershed catchments can be estimated using SRTM-based delineations of process-oriented model entities to get a suitable prediction of runoff dynamics with disposable landscape components in spite of an insufficient data base.

To make the approach applicable in Ungauged Basins a methodology is presented that is depend on the differentiation of landscape classes to allow a transfer to catchments with comparable relief characteristics. The transferability is essential for both the delineation of landscape dependent process entities (HRUs) and the parameterisation of model parameters for the distributed hydrological model J2000. The derivation of the HRUs is realised by a cluster analysis of the SRTM-derived relief indices under comprehension of other free global or trans-regional GIS data of the landscape components land use, soils and geology. Suitable relief indices combinations were selected with respect to process sensitivity and significance for the predominant landscape classes. The derived hydrological process units were joined topologically (1:n) for runoff routing and used as model entities for a comparative catchment modelling with J2000 in investigation areas of different relief characteristics in Germany and South Africa.

Due to the fact that a model calibration and validation in Ungauged Basins because of missing runoff time series is hardly possible, the range of the J2000 model parameters had to be reduced that the relevant parameters can be estimated a priori for each landscape type. A main goal of the developed method is the determination of model parameter selections that are especially significant and sensitive regarding to different landscape classes and relief characteristics in the catchments. The parameter sets are then transferred to catchments with comparable terrain roughness coefficient. This approach does not claim to provide an optimised configuration of the hydrological model. It offers a suitable basis parameterisation for the hydrological model run with J2000 in catchments with poor data availability on the base of available information of the relief and other landscape components.

Keywords: *SRTM, Hydrological Modelling, Prediction in Ungauged Basins, Hydrological Response Unit*

1. INTRODUCTION

Considering the increasing number of extreme hydrological events (flood and aridity) and the frequently discussed trends of global climate change the resource water attracts the scientific focus. Against the background of an inadequate water supply situation in developing countries and associated actual and future challenges for water management activities, there is a great demand to find solutions for the limited water availability. Distributive hydrological models are an important and useful instrument to include the requirements of a well adapted water management system considering local conditions. These models are based on the derivation of model entities for regionalisation of landscape characteristics. Integrated landscape elements are land use, soil, geology and particularly the relief and its geomorphological forming. Moore et al. (1992) observed that the topography of a catchment has crucial impact for all hydrological, geomorphological and biological processes in the landscape. Flügel (1996) expand this relief relation by connecting it with land use and other landscape components as expression of the landscape retention. The HRU regionalisation concept of catchments is realised by the intersection of data layers from the landscape parameters land use, soil, hydrogeology and indices derived from the DEM using Geographical Information Systems (GIS) operations. That so-called Hydrological Response Units (HRU) are topological connected model entities and represent areas of a homogeneous topographic and physiographic environment and determine the hydrological system response. In many river catchments of the world most of these required input data are only available on a coarse spatial resolution or insufficient quality. Furthermore, there is often a lack of data for discharge to run and validate hydrological models, so that the majority of all river catchments (circa 90 % worldwide) can be described as Ungauged Basins (Young and Romanowicz, 2004). The availability of precipitation data and climate data is an assumption for modelling nevertheless. The availability of new remote sensing products provides an opportunity to by-pass the problem of poor input data and offers a suitable GIS-database for regionalising river catchments based on HRUs.

Referring to a integration of Ungauged Basins in water management decisions and the availability of innovative global GIS data as well as the potential of distributive hydrological models, following key question can be asked for this research: *„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 this question should be answered by developing a topographic oriented HRU approach. For this intension the global and free SRTM-DEMs shall be used.

2. OBJECTIVES

Through the integration of remote sensing, GIS and distributive hydrological modelling using globally available SRTM elevation data, there is a promising opportunity to automate the HRU regionalisation concept based on unified topographical GIS derivations. The research is related to two research hypotheses:

(1) 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.

(2) It is expected that the landscape water balance of catchments with insufficient hydrometric infrastructure and data availability can be estimated and predicted using SRTM-based delineations of process-oriented model entities.

These hypotheses should be validated by the following objectives and working focus:

(i) Investigation of the scale comprehensive applicability of SRTM elevation data for delineating process relevant response units (HRU).

(ii) Compensation of missing adequate input data of other required landscape components through the development of a topographically oriented HRU-approach based on the integration of SRTM-derived topographic indices for the delineation of HRUs.

(iii) Hydrological modelling in catchments with different relief characteristics to identify sensitive landscape dependent model parameters using SRTM-based HRUs as regionalised model entities.

(iv) Estimation of close bounded model parameter ranges with relation to landscape classes to generate parameter configurations which can reproduce the hydrological dynamic in a defined domain of uncertainty.

(v) Transfer of the extracted model parameter configuration for modelling of the runoff dynamic in Ungauged Basins with the distributive hydrological model J2000.

(vi) Assessment of the analysis potential of SRTM-based modelling for simulating the landscape water balance in poor calibrated catchments by validating with available reference modelling data in South African.

A method will be provided to prepare and optimise SRTM elevation data for hydrological modelling of river catchments on the base of HRU regionalisation. Through comparative modelling studies in selected test catchments of different landscape classes in Germany and South Africa transferable model parameter configurations will be defined and adapted to catchment of corresponding relief characteristic. The model results will be validated by reference modelling data.

3. METHODS

3.1. Derivation of landscape oriented Hydrological Response Units

The distributive hydrological catchment modelling requires spatially related information about the distribution and characteristics of the relevant landscape components topology, land use, soil and geology to parameterise the model simulation. For mesoscale and macroscale catchments, the data can be acquired using remote sensing systems and handled by GIS systems (Becchi et al., 2001). The test sites of this research are located in the German river catchment *Saale* and its subcatchments *Obere Ilm*, *Bode* and *Helbe*.

Data preparation

Concerning the relief, the SRTM elevation data are a very valuable remote sensing product in view of Ungauged Basins. These data have a spatial resolution of approximately 90 m and 30 m, respectively (X-SAR-SRTM). SRTM data are an interferometric SAR product that underlies specific characteristics of generation technique. These radar specific effects limit their application for 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. The SRTM corrections include the elimination of areas with poor coherence, interpolation of data voids and filling of larger gaps with ancillary data. The hydrological conditioning was concentrated on water body corrections, hydrologically adapted filter combinations and the removal of flow barriers and flow depressions. to enable the runoff routing. Finally, hydrologically prepared and optimised SRTM elevation data were provided. Details to the hydrological preparation of the used SRTM elevation data are described in Pfennig and Wolf (2007).

Besides the relief, land use is an important landscape component for delineating HRUs. As this approach is dimensioned with relations to a global applicability, the innovative dataset GLOBCOVER was integrated. This ENVISAT MERIS product is a free and global land use classification system comprising 23 land use/land cover classes. For the derivation of HRU process entities a reclassification is needed with reference to the implemented land use parameterisation scheme in the applied hydrological model J2000.

Furthermore, there are trans-regional GIS datasets for soil and hydrogeology such as European Soil Database (ESDB) for Europe or the Soil and Terrain Database (SOTER) for Africa. However, the spatial resolution of 1 km for these data sets is too coarse to describe the catchment heterogeneity. Therefore, the main focus is laid on the topographic DEM derivations as primary component of HRU delineation. To parameterise the hydrological response units, all input datasets have to be prepared and reclassified in a model adequate classification scheme.

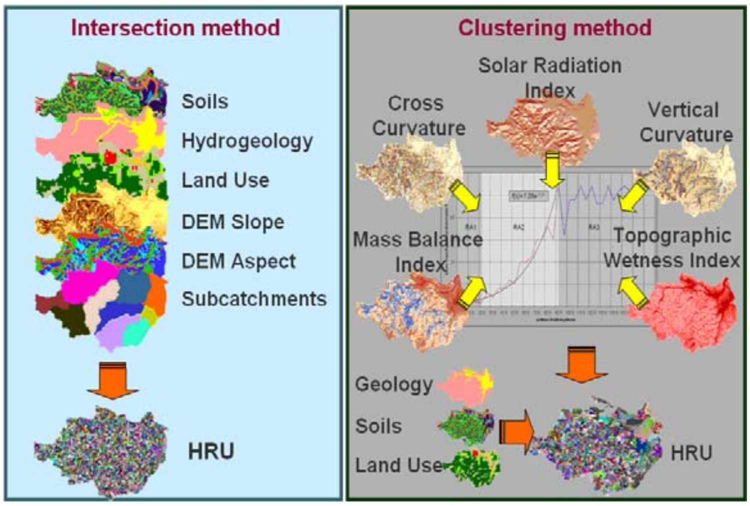

Figure 1. Comparison between the HRU derivation methods: Intersection of landscape components and topographically based clustering of topographic indices

Evaluation and clustering of landscape related terrain indices

The classic method of HRU delineation is realised by an intersection of the GIS layers of the several landscape components and their derivations. According to the guideline of the HRU concept after Flügel (1996) the relevant reclassified GIS layers are land use, soil, hydrogeology as well as slope, aspect and subcatchments derived from the DEM. The results are process entities as smallest common geometries. These HRU sub-areas shall be parameterised with regard to the hydrologically relevant processes, water storages and flow characteristics according to the J2000 input parameters. Because the global data basis of the landscape components soil and geology is to coarse for a useful implementation in the GIS intersection, a new approach is developed within this research to generate HRU geometries. That primarily relief related method is based on a clustering of selected terrain indices computed from the pre-processes SRTM DEM. Therewith, topographical HRU geometries will be obtained. Depending on research task and spatial resolution of the input data the information for land use, soil and geology can either be intersected afterwards or the attributes of these components can be assigned to the HRU entities after a statistical overlay matching. Figure 1 illustrates schematically the two described methods.

In the intersection approach slope is the most significant relief parameter because it affects surface runoff and interflow processes. However, there is no relation to the hillside curvature which is an important factor for spatial distribution of erosion or accumulation zones and flow convergences as soon as flow divergences of the runoff. Hence, the newly developed clustering approach integrates different relief parameters, such as Topographic Wetness Index, Mass Balance Index, Annual Solar Radiation Index and various curvature parameters (Table 1), which are all related to hydrological processes. The selection of the parameters used for the clustering is dependent on the significance of the processes in different landscapes and relief units.

Table 1. Selected relief indices for HRU derivation clustering and the relation to hydrological processes

Selected relief indices	significance for runoff processes
Slope	• velocity of surface runoff • quantification of solute transport processes
Tangential curvature	• reference to processes of runoff concentration, runoff acceleration and transport capacity of surface water flow • determination of erosions-, transit- und accumulation zones
Mass Balance Index	• relative index for determination of erosions-, transit- und accumulation zones • spatial variability of soil physical parameter
Topographic Wetness Index	• relief driven influence of topographically located saturation areas relating to runoff generation and dynamic • spatial distribution of soil moisture
Annual Solar Radiation Index	• improved relation to potential evaporation by integration of slope exposition and latitude

The objective was to integrate indices with higher significance for runoff processes than slope or aspect to increase the process delivery and the physical base. To make the quality of the approach assessable, the method was developed on a reference DEM from the Survey Agency with a raster resolution of 25 m. The potential of the indices to describe hydrological processes is highly scale dependent. Therefore, indices were selected which are process sensitive and also be transferable to the SRTM resolution of 90 m (Figure 2). Various indices were combined and different patterns of process driven HRUs for the diverse landscape classes were obtained. The selection and weighting of the relief indices for the clustering were dependent on the sensitivity in the prevailing landscape class. For example the Mass Balance Index is very appreciable in mountainous catchments, in flat areas the Topographic Wetness Index is more sensitive relating to the relevant hydrological processes of runoff, infiltration and evaporation. Thus a notable improvement in extrapolation of hydrological variables for model parameterization is aspired.

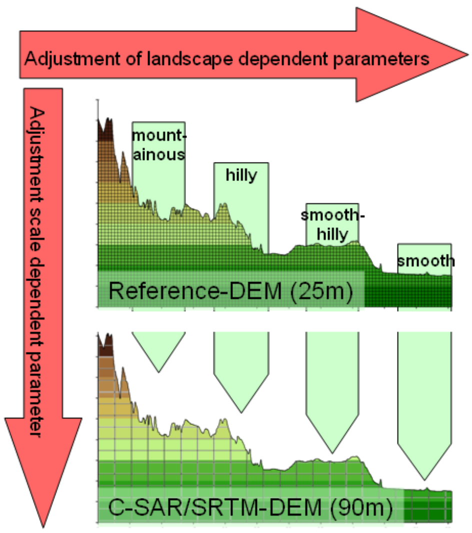

Figure 2. Evaluation of suitable relief indices relating to scale dependence and also landscape dependence in the cluster process

Comprehensible HRUs were delineated on the base of the selected terrain indices from SRTM elevations. 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. The median of all relief parameters highly correlates with the local relief amplitude calculated as range between highest and lowest elevation in a window (420 m × 420 m) and used as a representative roughness parameter for the respective landscape. In result, a well balanced differentiation of landform units will be achieved. So, the demarcation of local relief units can be optimised. More details to the process of HRU clustering are documented in Pfennig and Wolf (2007).

Figure 3 shows the results of derived HRU process entities in comparison. It becomes clear that the HRU geometries in the topographical HRU cluster method is more related to the runoff processes then the classic GIS layer intersection method. Valleys and hillside structures are good differentiated relating to runoff process delivery. In general, good results were reached in hilly and mountainous terrain. The shapes of erosion channels, ridges, river valleys and hillside forms were reasonably and plausibly delineated.

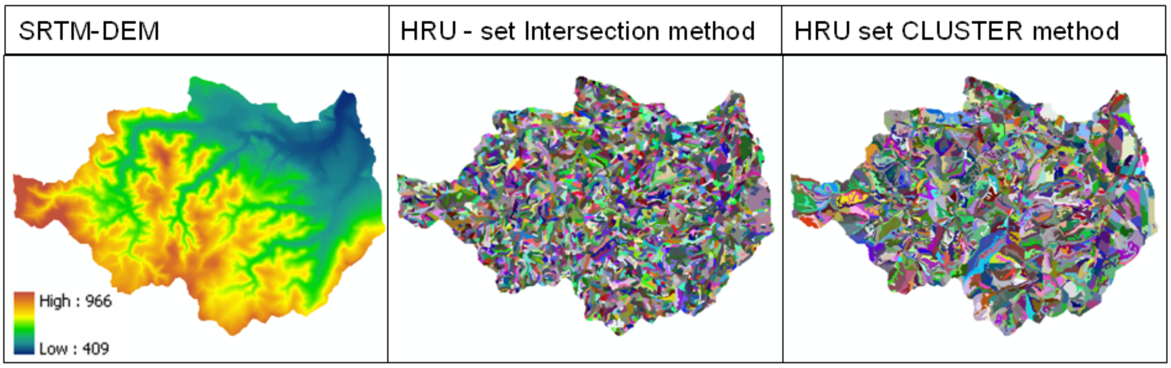

Figure 3. Comparison of HRU delineation between Intersection method and topographical cluster method in the catchment *Upper Ilm* (Germany)

3.2. Comparative hydrological modelling with J2000

The previously delineated HRU entities were afterwards topological joined (1:n) to enable the runoff routing and the HRU classes were parameterised for the input in the hydrological model J2000. This model allows a physically based and spatial distributed modelling of the water balance from mesoscale and macroscale river catchments. Besides the simulation of the hydrological processes, which affects the runoff generation and concentration, the model contains routines for the regionalisation of measured precipitation and climate station data. The simulated runoff results are a summing up the particular runoff components, which were separately calculated in the program modules. Regulations of the model execution takes place by the setup opportunities of 30 model parameters. Based on measured runoff data the model is to be calibrated in this way that the simulated runoff is adapted to the characteristics of the hydrological system in the catchment (Krause and Flügel 2001).

Evaluation of model sensitive landscape dependent J2000 parameters

A main goal of the comparative modelling was the determination of model parameter selections that are especially significant and sensitive regarding to different landscape classes and relief characteristics. Therefore following model configurations were prepared and run:

- **'Basis Modelling':** consists of HRU sets delineated by the classical intersection method based on DTM (25 m) and high quality data for land use, soil and geology for the German catchments *Upper Ilm* (mountainous), *Bode* (hilly) und *Helbe* (smooth)
- **'PUB Modelling':** topographical HRU sets delineated by the new cluster method based on SRTM-DEM (90 m), GLOBCOVER land use, soils and hydrogeology from the ESDB for the German catchments *Upper Ilm* (mountainous), *Bode* (hilly) und *Helbe* (smooth)

The arrangement of the landscape classes is based on the DEM calculation of the relief amplitude and terrain roughness in a moving window (420 m × 420 m) after the approach of Friedrich (1996). The three relief classes *mountainous*, *hilly* and *smooth* were defined by evaluated thresholds. The main objective consists in the evaluation of sensitive model parameters ensembles to adapt the parameter set to the respective relief characteristics. Starting point of the comparative analysis was a physically well tuned and calibrated model parameter set with very good efficiency values and adaptation to the measured runoff hydrograph. That set was used in a model run of the catchment *Upper Ilm* (landscape *mountainous*) for the 'Basis Modelling'.

(i) In a first step, this optimized parameter set was transferred to the 'PUB Modelling' consisting of SRTM-based HRU entities into the same catchment (*Upper Ilm*). The parameters were modified by a sensitivity analysis of each parameter to fit the hydrograph and the efficiency values. The adapted parameters were model sensitively related to the change in raster resolution from 25 m up to 90 m. Thereby, scale sensitive model parameters were identified und optimized. **(ii)** In a second step, the initial parameter sets were used again for a transfer to a 'Basis Modelling' of the catchment *Bode*, which has lower relief energy and roughness index then *Upper Ilm*. The landscape is classified as *hilly*. A manual calibration and sensitivity analysis were done to quantify potential relief sensitive model parameters. This step was continued in the catchment *Helbe* (characterised by a *smooth* landscape). In conclusion, an optimised model parameter set is available for each relief class. In this way an adapted parameter selection of six model sensitive landscape dependent parameters could be isolated. The extracted J2000 parameters are described following:

FlowRouteTA	velocity coefficient of the runoff wave in the channel
LatVertLPS	distribution coefficient of water from large pore storage to interflow and percolation
outLPS	outlet coefficient of the large pore storage of soil
MaxPerc	maximum daily percolation rate
ConcRD1/ConcRD2	retention coefficient of direct surface runoff and interflow
RG1fact/RG2fact	factors for the dynamic of upper and lower ground water storage

The extracted sensitive parameter from (i) and (ii) were summarized together to a 'PUB model parameter selection' and ensample were determined, that enables a transfer of the optimized model configuration from the 'Basis Modelling' to the 'PUB Modelling'. This predefined J2000 parameter sets should be adaptable for Ungauged Basins on the base of relief classes to a good approximation of the catchment runoff reaction and adequate model results in spite of missing validation opportunities.

4. RESULTS

The extracted 'PUB model parameter selections' were applied to a 'PUB Modelling' approach in each of the three German catchments. The 'PUB Modelling' is containing the topographical HRU entities, which were delineated by the new cluster method based on SRTM-DEM and global GIS data for land use (GLOBCOVER), soil (ESDB) and lithogeology (ESDB). So, virtual PUB conditions were simulated. Deviations in the simulated runoff hydrograph in comparison to the 'Basis Modelling' are caused by varied geometries of the process entities and the changing input data of the landscape components. It is comprehensible that efficiencies of the PUB model approach can not reach the value of the 'Basis modelling' because of the input data. But a well approximation was reached. In Table 2 the J2000 efficiency values of 'Basis Modelling' and 'PUB Modelling' in the German catchments of various landscape are compared. The Nash-Sutcliff-Coefficient (e^2) is especially sensitive for runoff peaks and fast runoff components. The logarithm of (log_e^2) is an indicator for the simulation of ground water drainage in contrast. The coefficient of determination (R^2) indicates the rendering of the temporal dynamic of simulated runoff process.

Table 2. J2000 efficiency values for 'Basis Modelling' with reference DTM and 'PUB Modelling' configuration on the base of global input GIS data (Time period: 01.11.1980 – 31.10.1983)

Efficiency	**landscape class / catchment**					
	mountainous / *Obere Ilm*		hilly / *Bode*		smooth / *Helbe*	
	Basis modelling DTM (25 m)	PUB modelling SRTM (90 m)	Basis modelling DTM (25 m)	PUB modelling SRTM (90 m)	Basis modelling DTM (25 m)	PUB modelling SRTM (90 m)
e^2	0.83	0.79	0.63	0.56	0.54	0.49
log_e^2	0.88	0.76	0.50	0.41	0.52	0.42
R^2	0.84	0.75	0.70	0.64	0.65	0.61

In the mountainous catchment *Obere Ilm* the best model results were reached. General, a very good adaptation of measured and simulated runoff were found in this catchment. The efficiencies of the 'PUB Modelling' look also well but little worse than the 'Basis Modelling'. This clarified that the heterogeneity of the catchment in spite of the coarser spatial raster scale of the GIS input data were reproduced adequate enough to simulate the hydrological runoff dynamic by the physical model structure of J2000. That takes effect in the other catchments too. But it is notable, that the model efficiencies in catchments of lower relief class degrease. Summarising, on the base of the global input data and usage of the clustered SRTM based terrain indices satisfactory model results were reached. That indicates a reasonable simulation of spatial and temporal runoff processes on the base of SRTM data and other free global GIS data sets under usage of predefined landscape oriented J2000 model parameter sets is possible. What matters is that it is feasible to describe the relevant hydrological processes sufficing through the physical model structure of J2000.

5. DISCUSSION AND CONCLUSION

SRTM offers a solid base for mesoscale and macroscale hydrological oriented applications in most parts of the world. The investigation of the potential of SRTM data for delineation of process relevant response units over various scales was one important aim of this research. An optimisation of the elevation data was therefore required to improve the SRTM topology for hydrological applications. Numerous topographic indices were applied on these data whereas the index selection was oriented on different relief driven processes. The resulting datasets were analysed by the Cluster Analysis IVHG. By combining various topographic indices, different patterns of process driven HRU were delineated. These HRU-sets were used as input entities in the hydrological model J2000. As result of the comparative modelling analysis, universal J2000 model parameter sets for the relief classes *mountainous*, *hilly* and *smooth* were provided for use in Ungauged Basins. In a next step of this research the acquired and post-calibrated ‘PUB model parameter selections’ from the three German test sites will be transferred to catchments in South Africa with corresponding landscape characteristics. Corresponding catchments pairs are *Upper Ilm - Mooi*, *Bode - Letaba* and *Helbe - Sandspruit*. As a simulation of PUB conditions a ‘PUB Modelling’ of the South African catchments will be initiated. SRTM-DEM and CLOBCOVER data were also used there as GIS input data for the derivation of topographical indices and daily runoff measurements and comparative hydrological model results are available. By means of these comparative model results the quality of the ‘PUB Modelling’ can be validated and derivations can be interpreted. Further tests to transfer the ‘PUB model parameter selections’ are in planning for test sites in the *Brahmaputra* catchment and in the *Alps* (Austria) to prove and optimise the methodology and get a differentiation relating to landscape and climate dependent catchment characteristics. So a wider sampling of predefined parameter sets will be created.

With the global SRTM elevation data the opportunity exists to extend the developed topographical HRU regionalisation concept in a scale comprehensive way by unified topographic GIS derivations. Consequently, the approach will be transparent and reproducible relating to comparative studies with similar objectives in other catchments. Comparative modelling of ‘PUB modelling’ and ‘Reference modelling’ in the South African catchments will show, which explanatory potential for the hydrological dynamic of landscape water balance alone from the landscape components (primary relief) can be evaluated. Narrow ranges for the J2000 parameters shall be determined to get the possibility of *a priori* parameter estimations. So, hydrological processes in poor calibrated models under PUB conditions can be simulate on the base of these ensemble calculations. But this approach provides not the claim of a finalised calibrated hydrological modelling. It should a suitable basis parameterisation for the hydrological modelling in catchments with poor data availability on the base of available information about relief and other landscape components.

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