Applying Different Concepts of Hydrological Response Units (HRUs) in Three Nested Mesoscale Catchments for Distributed Hydrological Modelling

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Abstract: Distributed physically based river basin models are receiving increasing importance for integrated water resources management (IWRM) in Germany and in Europe especially after the release of the new European Water Framework Directive (WFD). Applications in mesoscale catchments require an appropriate approach for representing the spatial distribution of related catchment properties such as land use and topography by utilizing techniques of remote sensing and GIS analyses. The challenge is to delineate scale independent homogeneous modelling entities which on the one hand represent the dominant hydrological process dynamics and on the other side can be derived from spatially distributed physiographical catchment properties. This challenge is met in this regional modelling study by applying the concept of Hydrological Response Units (HRUs). In a nested catchment approach three different modelling conceptualisations are used to describe the runoff processes. Using different conceptualisations to link the HRUs these approaches model consider lateral flows in various ways. Simulations show that the physiographic based concept was found to be a reliable method for modelling basin dynamics in catchments up to 200km² whereas in bigger sized catchments where lateral processes are dominating both other concepts have advantages.

Keywords: Regionalisation; Hydrological Response Units; Mesoscale Distributed Modelling; Parameter Transfer

1. INTRODUCTION

Hydrological Model Development in the past has led to a great variety of different Models and Modelling Systems differing conceptually depending on the purpose they had been developed for. Singh [1995] gives an overview about hydrologic models frequently applied in meso- and macroscale river basins. Models such as TOPMODEL [Beven et al. 1995], SHE [Abbott 1986] and the IHDM [Beven et al. 1987] are physically based, use grids, Representative elementary areas and subbasins as modelling entities and therefore are applicable on the micro- and lower mesoscale scale. There is the problem of transferring microscale approaches to meso- or makroscale because the relevance of hydrologic processes may change at scale transition and thus implies that modelling concepts which have been developed for the microscale can not be used on larger scales offhand [Peschke et al. (1998)]. Besides that microscale Models needs data which in larger basins are often not available in the postulated level of detail. Even if microscale concepts do not exclude the use on meso- or macroscale, their origin physical basis would be restricted by the fact, that model parameters are not measured but estimated. However, large scale modelling requires a more flexible approach for catchment distribution such as the HRU concept [Flügel 1995] applicable within the scope of a nested catchment approach. HRU are scale independent modelling entities cause they are based on physiographic parameters. Models such as PRMS [Leavesley et al. 1983], SWAT [Srinisavan & Arnold 1993] and J2000 [Krause 2001] meet the criteria of being distributed, physically based and process oriented. The recent release of the European Water Framework Directive (WFD) recently has reinitiated this discussion for benchmark modelling of large scale river basins. Models such as WaSiM-ETH [Schulla 1998], HBV [Bergström 1992] and J2000 [Krause 2001] can be listed in that context However, the distribution concepts of these models differ quite substantially ranging from simple semi-distributive approaches (HBV) to explicit, process oriented approaches (WaSiM-ETH, J2000). Different model concepts have to be tested on various catchments to get an idea which concept is the best for which catchment size.

2. OBJECTIVES

The objective of the study is the test of different distribution concepts representing the catchment's physiographic heterogeneity and hydrological dynamics best. The distribution concept of Hydrological Response Units (HRUs) as presented by Flügel [1995] and Leavesley et al. [1983] is applied and furthermore refined by integrating the topology of the HRU-subareas for flow routing thereby integrating vertical and lateral transport processes of the hydrological cycle. HRU are delineated within a GIS by means of criteria defining a minimum set of required input information. The HRU concepts described later in this paper were tested applying an integrated approach of empirical field studies, GIS analyses and remote sensing data. The scale oriented objectives were to **(i)** investigate pros and cons of the different HRU concepts, **(ii)** test the transfer of model parameter, and **(iii)** check in how far process dynamics change during upscaling. The study was part of the RIVER project carried out by the Thuringian Environmental Agency and the Department of Geoinformatics, exploring the operational use of remote sensing techniques for nature conservation, regional planning and water resources management.

3. STUDY AREA

The Ilm catchment is located in the middle part of the state of Thuringia, Germany.

It stretches from its headwater located in the middle mountain range of the Thuringian Forest to the Thuringian lowlands. The river drains a basin of 1025 km^2 of which 895 km^2 are measured by the gauge located in Niedertrebra (Figure 1).The climate is characterized as the transition zone between wet oceanic and dry continental climate. Spatial rainfall variation ranges from 1200 mm in the Thuringian Forest to only 500 mm in the flat lowlands. The mean annual river discharge is 6,3 m^3/s. After 135 km flowing towards northeast the Ilm drains into the Saale river. The land use is very heterogeneous, but mirrors somehow the geological and landscape structure. Coniferous forests dominates the headwaters of the Thuringian Forest, and changes towards intensive agriculture in the Thuringian lowlands. Three dominant soiltypes can be differentiated: **(i)** Brown Soils, sometimes hydromorphic, in the Thuringian Forest, **(ii)** Rendzina Soils on limestone, and (iii) Gley Soils in the valley floors.

4. METHODOLOGY

A GIS database including all physiographic catchment properties such as land use classified from IRS-1C Data, soils, geology, and topography was established for the HRU delineation.

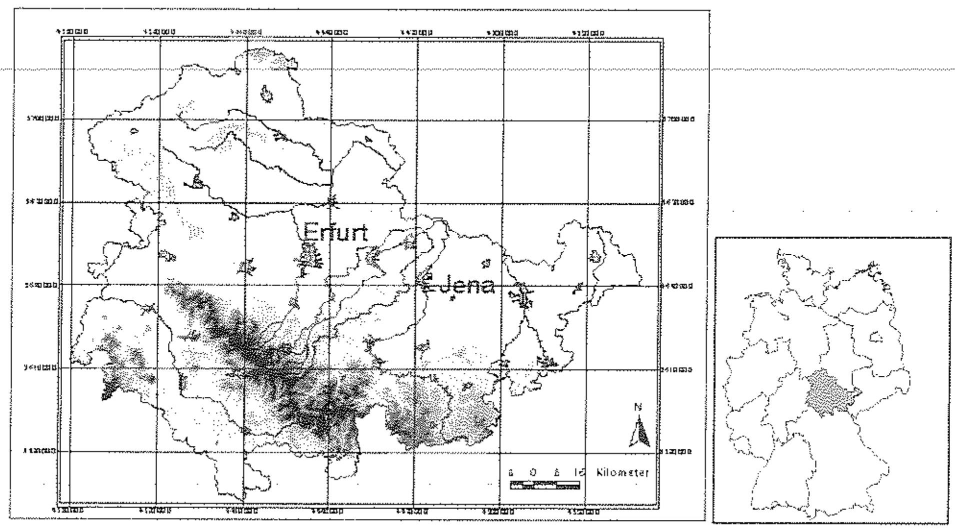

Figure 1. Location of the Ilm catchment in Thuringia.

Precipitation data from sixteen rain gauges, temperature, snow and radiation data from two meteorological stations and altogether three gauging stations along the Ilm river were available for the hydrological modelling.

4.1 Hydrological System Analyses and HRU

An integrated systems approach is essential for analysing and modelling the hydrological dynamics of such heterogeneous structured river basins. Especially the process interactions within the Soil-Vegetation-Atmosphere (SVA) interface are very complex and important for runoff generation of the entire basin system. They are schematically shown in Figure 2 and are accounted for by PRMS within the SVA-interface.

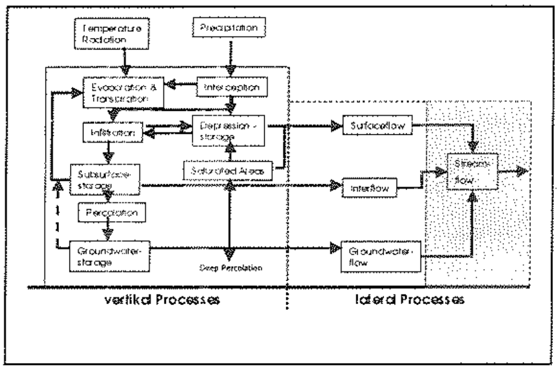

Figure 2. Schematic of water storages and processes within the soil-vegetation-atmosphere interface

The concept of Hydrological Response Units (HRU) is based on the hydrological system analyses. The latter provides process oriented criteria to delineate them as distributed land units, which comprise a specific assembly of components characterizing the catchments natural and human environment [Flügel 1995]. As these components, such as the pedo-topo-geological-sequence control the dominant hydrological and solute transport processes HRU can be applied as distributed model entities. They conserve and represent the complex and distributed three-dimensional environmental basin heterogeneity and are characterized by the fact, that the variation of the hydrological dynamics within each HRU subarea is small if compared to neighbouring ones. According to the location of the gauging stations located at the Ilm river the catchment was divided into three nested subcatchments each having a drainage size of 154 km^2, 627 km^2, and 895 km^2 respectively. HRU were delineated for each subcatchment with the same procedure so that only the number of HRU differ cause of changing catchment characteristics. Using three different approaches these modelling entities consequently were parameterised in PRMS. Results were evaluated according to their ability for representing the hydrological dynamics in the three subcatchments and for parameter transfer between them.

4.2 HRU Delineation Using GIS-Analyses

HRU were delineated within the GIS according to three different concepts:

(i) For the delineation of ***process oriented HRU*** according to Flügel [1995] GIS data layers representing the three dimensional heterogeneity of the System were overlayed by means of a GIS (Figure 3). A threshold value of 2 % of the total catchment area was used to limit the number of HRU classes obtained to a reasonable size. All classes smaller than the threshold were merged with larger, similar ones. Finally 36 HRU were delineated for the whole catchment (Figure3).

Advantage:

- scale independent and process oriented parameterisation of modelling entities

Disadvantage:

- modelling of lateral flows is not conceptualised

(ii) The delineation of ***topographic based HRU*** according to Leavesley et al. [1983] was done using the GIS-Toolbox Weasel. Based on a DEM the flow direction is computed with a consequent delineation of a stream network. The segments of the latter are used for the delineation of left and right flowplanes along the different tributaries. Finally 54 flowplanes were delineated as HRU (Figure 3). As this delineation is based only on the topographical system characteristics all HRU are linked hierarchically.

Advantage:

- lateral processes could be taken into account

Disadvantage:

- physiographic properties are parameterised inaccurate, only one to one routing is possible

(iii) The HRU approach presented in (i) was extended by a topological component developed by Staudenrausch [2000]. It integrates the topological flow routing between HRU subareas into this process based distribution concept (Figure 3). The first step in deriving the topology was the generation of the reach-to-reach-connectivity within the stream network using the GIS-internal arc-node topology information. In a second step the connectivity between the HRU subareas and the stream network was generated. This condition is fulfilled if a HRU-subarea polygon is intersected by a stream network segment. All other polygons not adjacent to a stream had to be associated with their downslope neighbouring HRU-polygons they are draining into. In the final topological assembly all HRU-subarea polygons either drain downslope in neighbouring polygons or directly into their adjacent river segment. The topological HRU-concept thereby permits the simulation of vertical fluxes into the soil and lateral fluxes within the hillslope.

5. MODEL APPLICATION

The modelling system MMS/PRMS a deterministic, distributed and continuous water balance model was applied for the simulation of the hydrological catchment dynamics. The different modules of PRMS are physically based and simulate the vertical and lateral processes present in the various HRU. The parameterisation for all modelling entities was derived from the GIS layers used to delineate the different HRU described above, and was kept constant for all of them. All three HRU approaches were used in the two subcatchments of the Ilm river: **(i)** the headwater basin up to gauge Gräfinau-Angstedt, and **(ii)** the whole catchment up to the gauging station Niedertrebra.

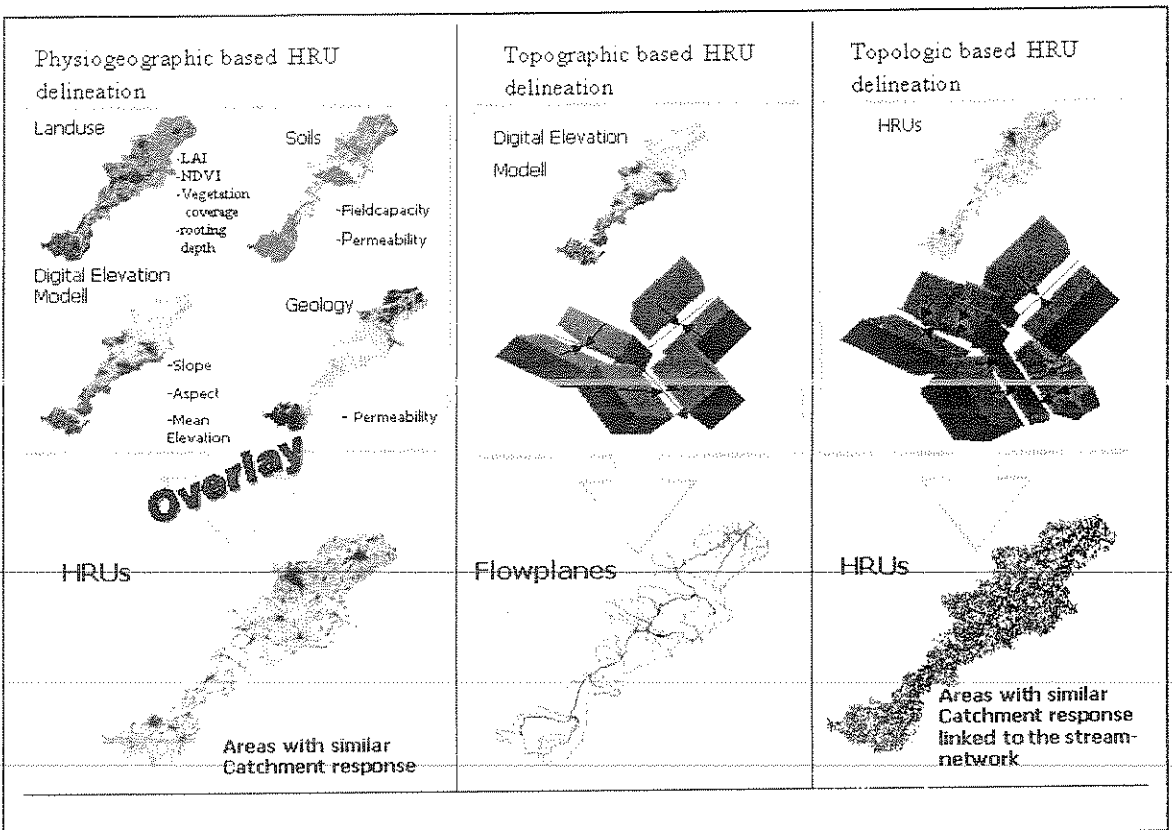

Figure 3. Different HRU-delineation approaches

5.1 Modelling Results Obtained by Applying the Physiographic Based HRU Approach

As shown in Figure 4 for the hydrological year 1981 the visual inspection of the simulated and observed discharge time series for the 22-year daily simulation period shows a reasonable good fit most of the time.

The fit was described for the different years by correlation coefficients ranging between 0.78 (gauge: Niedertrebra) and 0.90 (gauge: Gräfinau-Angstedt). In general the results obtained by using the physiographic HRU seems somehow to be dependent on the catchment size as the correlation as well as the model efficiency and the log. efficiency tend to be less good with increasing catchment size.

The climatic conditions obviously have major influence on the simulation results as i.e. the hydrological year 1988 in both catchments shows good fits and seems to have the optimal climatic conditions for the selected model parameterisation. In general PRMS/MMS tends to **(i)** underestimate advective storm hydrographs caused by rainfall on snow covered areas, **(ii)** precipitation mixtures of rain and snow during the winter, and **(iii)** base flow in summer during long dry weather periods. Interflow was simulated as the dominant runoff component from the forested slopes in the headwater catchment till the gauging station Gräfinau, and also on the agricultural used gentle slopes downstream till the gauging station Niedertrebra.

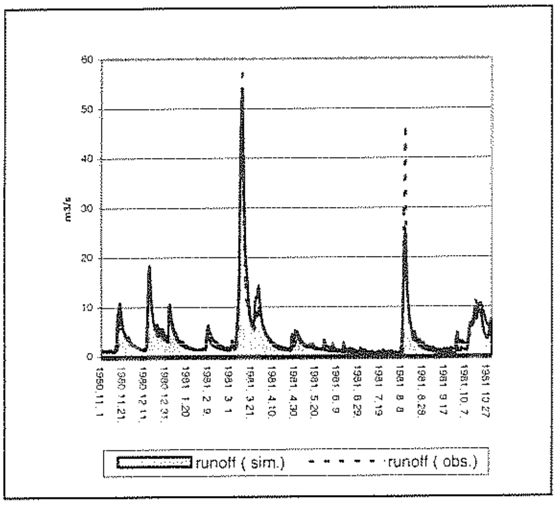

Figure 4. PRMS simulation using the physically based HRU approach for the upper Ilm Catchment till gauge Gräfinau for the hydrological year 1981.

5.2 Modelling Results Obtained by Applying the Topografic HRU Approach

The topographic based HRU approach is considering lateral overland flows but is neglecting the real distribution of physiographic properties controlling the hydrological dynamics within the flow planes. The fit between simulated and observed discharge for the 22-year daily simulation period produced similar results as the physically based HRU approach. Such a fit is shown in Figure 5 for the hydrological year 1979.

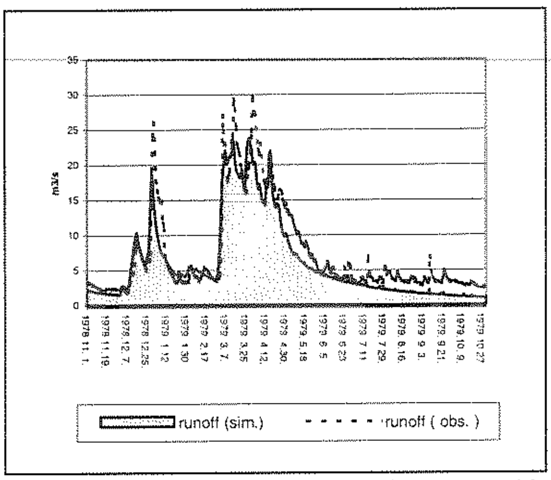

Figure 5. PRMS simulation using the topographic based HRU approach for the Ilm catchment up to gauge Niedertrebra in the hydrological year 1979

Simulation of the complete data set in the whole catchment results in correlation coefficients ranging from 0.64 (1987) up to 0.93 (1989). However, if one looks at the total time span modelled for the catchment up to the gauging station Niedertrebra (A = 895 km^2) the model efficiencies of 0.72 are clearly lower than obtained with the physiographic HRU approach. Obviously lateral flow is not compensating the deficiencies resulting from neglecting the influence of land use pattern.

5.3 Topologic Based Modelling Approach

For the topological based modelling approach the parameterisation work is still in progress and only first results can be presented. They indicate that simulation results will become better than the physiographic based approach. The comparison of the simulated and observed discharge for this period shows a pretty good fit most of the time. As an example the runoff of the water year 1979 is shown in Figure 6.

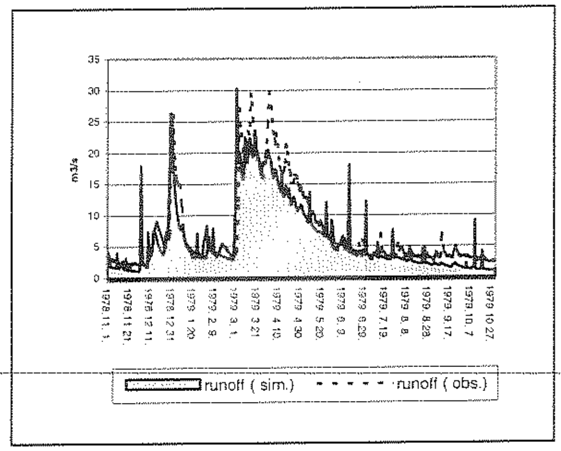

Figure 6. PRMS simulation using the topologic approach for the Ilm catchment up to gauge Niedertrebra in the hydrological year 1979

Simulation of the 5-years calibration period showed correlation coefficients ranging between 0.76 and 0.87 in Niedertrebra. They prove the advantage of linking vertical and lateral flows in heterogeneous mesoscale catchments. However, it also became clear from the modelling results, that the new approach requires improved parameterisation and probably improved process modules. This was interpreted from the facts, that years with low flow periods had good fits, meanwhile years with frequent hydrographs showed bad fits between the simulated and observed discharges.

6. CONCLUSIONS

The results obtained from the modelling exercises must be interpreted referring to the hydrological dynamics of the catchment on the one hand and the distributed approaches applied on the other.

The upper headwater catchment of the Ilm river down to the gauging station Gräfinau is underlying by almost impermeable bedrock, meanwhile the limestone in the middle part of the catchment is characterized by a distinct Karst dynamics. As a result the middle part of the catchment experiences considerable water losses out of the river bed into the Karst system. Such water losses have shown to be diverted into neighbouring catchments, but very little is known about the total daily water losses. Consequently PRMS is not able to handle these dynamic losses and this fact is influencing the simulation accuracy of all HRU trials.

The distribution of daily precipitation within the catchment is quite variable and is mainly controlled by the topography and the prevailing wind direction. The Thiessen polygons used as a regionalisation method are not accounting for these effects and probably supply unprecise daily rainfall input values. All modelling entities have been parameterised according to their physiographic properties and the parameters have kept constant so that we assume that parameter transfer from one catchment to another within the mesoscale is possible

The three applied HRU-approaches differ in terms of accounting for vertical and lateral flow processes. The most efficient concept in this respect is the topological-physiographic HRU approach.

The modelling exercises revealed that model parameterisation is strongly dependent on the physiographic variability within and between the three nested sub-basins. However, each HRU concept applied proved to be sensitive towards land use changes when generating associated runoff. The holistic physiographic HRU concept proved to yield better results if compared with the topographical HRU flow planes for the catchment less than 200 km^2. The topological HRU approach, however, provided improved simulations in larger basins. As the topological networking of HRU-subareas accounts for vertical and lateral hydrological processes it seems to be a more realistic way to represent the distributed hydrological dynamics of large scale catchments without multiplying the effort necessary to obtain a realistic parameterisation.

7. ACKNOWLEDGEMENTS

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