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Combining GIS with regional hydrological modelling using Hydrological Response Units (HRU's) - An application from Germany

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Abstract The concept of **Hydrological Response Units (HRU's)** and their delineation and application to the Bröl catchment (A = 216 km^2) in Germany is presented. HRU's are object orientated model entities and can be used within the PRMS/MMS hydrological catchment model. Applying the HRU-concept to the Bröl catchment altogether twenty-three different HRU's were delineating from a DEM (50 x 50 m grid size), three classified pedo-topo-geological associations and four dominant land use classes. The model was then run with these HRU's using a twenty-year daily data time series. The model parameterization was carried out in such a way that rainfall input not consumed by evapotranspiration was routed to a common conceptual subsurface storage, which drained by interflow towards the shallow groundwater aquifer in the valley floors, which in turn drained to the channel network. The model fit between simulated and observed discharge was good (r = 0.91) and the sensitivity analysis revealed that the model was sensitive to parameters directly related to the land use. Future research activities will concentrate on applying the model for drainage basins of different climate and also will focus on the spatial distributed precipitation for HRU-classification and the object orientated linkage of the HRU's within the catchment and on integrating object design in hydrological models.

1. INTRODUCTION

During the last decades hydrologists have focused their attention on the processes comprising the hydrological dynamics and runoff generation (Hewlett & Hibbert, 1967) of river basins. The heterogeneous distribution of the physiographic basin characteristics, such as precipitation, topography, soils, geology and land use, controls infiltration, surface runoff and evapotranspiration, (Anderson & Burt, 1979; Beven & Kirkby, 1979), and is imbedded into the theory of regional hydrological modelling (Beven et. al., 1988). In mountainous basins interflow in the hillslopes is of paramount importance for groundwater recharge and the generation of river runoff (Anderson & Burt, 1990; Binley & Beven, 1992; Flügel, 1979, 1993; Kirkby, 1978). The drainage basin therefore must be seen as a heterogeneous assembly of distributed entities having specific physiographic properties and precipitation input, each contributing differently to the basin's output. These entities are described by Flügel (1995) as Hydrological Response Units (HRU's) and can be understood as hydrological objects characterized by a certain assembly of these physical properties.

Models accounting for this heterogeneity must (i) simulate the physical processes either by applying physical laws (if they are already known) or established empirical relationships from field studies (Flügel, 1979); (ii) be modularily structured to permit module adaption for various hydrological dynamics in different climatic environments; and (iii) be object orientated designed to be capable to handle hydrological objects.

The PRMS/MMS model developed by the U.S. Geological Survey (Leavesley et al., 1983) used in this study fulfills the first two conditions, and combined with a GIS (Moore, 1993; Maidment, 1991) provides a set of tools for modelling heterogeneous structured drainage basins (Flügel & Lüllwitz, 1993). Recent model development carried out be the authors research team is focussing on the object orientated modelling development as introduced by David (1995).

2. OBJECTIVES

The objectives of the study, which is part of a long term sytems analysis of the Sieg drainage basin were five-folded: (i) To further develop the concept of HRU's; (ii) present the method of GIS analysis to delineate HRU's based on the hydrological systems analysis; (iii) apply the GIS-method to delineate HRU's to the test basin of the River Bröl; (iv) use the HRU's in PRMS/MMS to simulate the hydrology of the Bröl basin for a 20-year data set; and (v) identify further research needs to improve the modified HRU concept.

3. BASIN HETEROGENEITY AND HRU-CONCEPT

A systems approach is essential for analyzing and modelling the hydrological dynamics of heterogeneously structured drainage basins, and especially the processes interacting within the Soil-Vegetation-Atmosphere (SVAT) interface are of paramount importance. The SVAT-interface influences evapotranspiration, infiltration, surface runoff, interflow, groundwater recharge and runoff generation of the entire river basin. The "real world" of such a basin segment, and the interlinked water fluxes through its topography are schematically shown in Fig. 1. The three-dimensional physiographic heterogeneity in terms of topography, soils, geology and land use can be grouped together into associations. Topography, soil types and geology are interlinked due to processes of weathering and erosion and form topo-pedo-geological association. For example a gley soil will be found at the valley floor with shallow groundwater, but rarely on the plains, and certainly not on the slopes. As general land use classes agriculture, rangeland, forest and impervious areas with different rooting depth in third dimension can be differentiated. However, land use and the topo-pedo-geological associations show characteristic linkages as well as agriculture prefers fertile, deep developed soils in the valley floor and on gentle hills, while rangeland and forests are restricted to shallow, less productive soils on the slopes and on the plains. As can be seen from Fig. 1 each land-use class is located on a specific pedo-topo-geological association forming a unique entity in the basin.

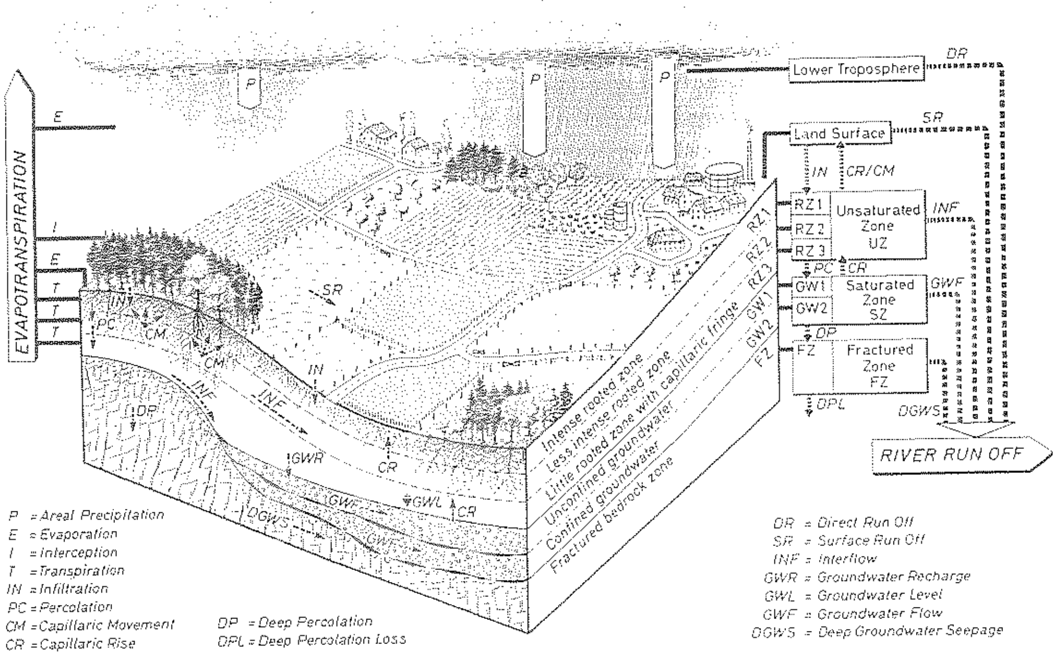

Fig. 1 Schematic view of the water fluxes within a river basin segment

The basic assumption is that each of these entities also has a unique hydrological dynamics controlled by their land-use management and the physical properties of the underlying pedo-topo-geological association. They are then defined as Hydrological Response Units:

"Hydrological Response Units are distributed, heterogeneously structured areas with common land use and pedo-topo-geological associations controlling their unique hydrological dynamics"

The crucial assumption based on the systems analysis for each HRU is, that the variation of the hydrological dynamics within it are small compared with the difference to a neighboring HRU. They can therfor be adressed as hydrological objects and can be treated within a object orientated model accordingly.

4. RESULTS

4.1 Bröl basin and data base

The drainage basin of the River Bröl (A = 216 km^2) is located east of the River Rhine in the middle mountain range of the Rheinische Schiefergebirge, Germany. It can be seen as a representative tributary of the Sieg river catchment (A = 2832 km^2). The region has an oceanic climate and rainfall varies with elevation between 800 and 1200 mm. During summer convective storms are frequent and during winter advective rainfall is dominant. The underlaying geology is impermeable Devonian shale, and deep percolation is negligible. The soil catenas consists of high plains with hydromorphic brown soils, adjacent slopes with brown soils and small valley floors with gley soils. A twenty-year hydro-meteorological daily data base with rainfall (6 stations), temperature, radiation and discharge observations (each 1 station) was available for the modelling study.

4.2 Hydrological Systems Analysis

The drainage basin was intensively studied during various field campaigns and additionally the available hydro-meteorological data base was analyzed. From these studies the hydrology of the basin can be described as follows: (i) Surface runoff occurs only during extreme winter snow melt events often on frozen soil surface, or extreme summer storms with high rainfall intensities; (ii) rainfall is buffered by interception of the forest and grassland vegetation, and the soil infiltration capacity can mostly account for the throughfall; (iii) the infiltrating water is stored in the unsaturated root zone for consumption by evapotranspiration, and if field capacity is exceeded, water percolates further downwards creating a wetted zone above the underlying impervious bedrock; (iv) if coarse pores (earthworms, former root channels, etc.) are frequent, this slower percolation process is enhanced by the fast downwards flow of water from the surface towards this

HRU No.	Area (km²)	Area (%)	Av. Elev. (m aSL)	Toposequence	Slope (%)	Soil Types	Land Use	Aspect N,E,S,W
1	23.4	10.9	213.1	all	all	all	imperv.	all
2	3.2	1.5	235.4	plains	0 - 10	hy_brs	forest	N - E
3	4.0	1.9	230.5	plains	0 - 10	hy_brs	forest	E - S
4	5.6	2.6	231.9	plains	0 - 10	hy_brs	forest	S - W
5	5.4	2.5	237.7	plains	0 - 10	hy_brs	forest	W - N
6	3.3	1.5	239.0	slope	10 - 20	brs	forest	N - E
7	5.2	2.4	214.6	slope	10 - 20	brs	forest	E - S
8	5.2	2.4	197.2	slope	10 - 20	brs	forest	S - W
9	7.6	3.5	190.7	slope	10 - 20	brs	forest	W - N
10	13.8	6.4	211.5	slope	> 20	brs	forest	N - E
11	10.7	4.9	213.8	slope	> 20	brs	forest	E - S
12	8.8	4.1	153.8	slope	> 20	brs	forest	S - W
13	5.0	2.3	219.0	slope	> 20	brs	forest	W - N
14	13.1	6.1	213.0	valley	0 - 10	gley	forest	all
15	15.8	7.3	217.8	plains	0 - 10	hy_brs	grassl.	N - E
16	9.9	4.6	223.9	plains	0 - 10	hy_brs	grassl.	E - S
17	4.4	2.1	227.5	plains	0 - 10	hy_brs	grassl.	S - W
18	6.4	3.0	208.9	plains	0 - 10	hy_brs	grassl.	W - N
19	10.0	4.7	204.7	slope	10 - 20	brs	grassl.	N - E
20	18.0	8.4	207.1	slope	10 - 20	brs	grassl.	E - S
21	9.8	4.5	216.2	slope	10 - 20	brs	grassl.	S - W
22	8.5	3.9	214.6	slope	10 - 20	brs	grassl.	W - N
23	18.2	8.5	174.9	valley	0 - 10	gley	grassl.	all

Abbrev.: m aSL = meters above sea level; imperv. = impervious; grassl. = grassland; hy_brs = hydromorphic brown soil; brs = brown soil

Tab. 1 Hydrological Response Units (HRU's) derived by GIS-analyses for the Bröl catchment

zone: (v) interflow in the shallow soils of the slopes is the predominant hydrological dynamic in the basin, and frequently was observed in the field during storms; (vi) groundwater is restricted to the valley floors and is recharged by percolation from the unsaturated zone above, but the majority of its recharge is received by interflow from the adjacent slopes.

4.3 HRU delineation using GIS overlay analysis

The GIS database was generated by digitizing maps of soil types and land use, and by importing a DEM into the GIS. The digitized vector files were then imported into the GIS and transferred into raster files to be used in the overlay analyses. The HRU's were delineated by GIS-analyses as follows: (i) slopes and aspect were derived from the DEM; (ii) topography soils and geology were grouped into the four different pedo-topo-geological associations of plains (0 - 10% slope and hydromorphic brown soils), slope 1 (10 - 20% and brown soils), slope 2 (> 20% and brown soils), the valley floor (> 0% and gley soil); (iii) areal mean daily precipitation was calculated from Thiessen polygons and was applied uniformly to all HRU's; (iv) four land use classes of forest (mixed deciduous and coniferous stands), grassland, agriculture and impervious areas were classified. During the GIS overlay analysis, generated subclasses with small areas were merged with similar larger classes based on the insight gained by the hydrological systems analysis. Using the entire GIS data base, 23 HRU's were delineated listed together with their physiographic properties in Tab. 1.

4.4 Applying the HRU's in the PRMS/MMS model

The twenty-three HRU's of the Bröl basin were tested using the hydrological basin model PRMS/MMS developed by the U.S. Geological Survey (Leavesley et al. 1983; Flügel & Lüllwitz, 1993). The modelling exercise was carried out in the following way: (i) the first two years were used as an initialization period; (ii) the driest and wettest years were selected for calibrating the parameters for best fit between simulated and observed discharge; (iii) parameter optimization and sensitivity analysis was done using the 1980 - 1985 data; (iv) parameter validation was carried out by running the model with the complete 20-year data set. Interflow was represented in the model control file by parameterizing the unsaturated subsurface reservoir of each HRU on the slopes and the plains to drain either directly to the river channel or recharge the groundwater reservoir in the valley floor. The flow chart of the interlinked HRU's located on the three toposequences of the high plains, the

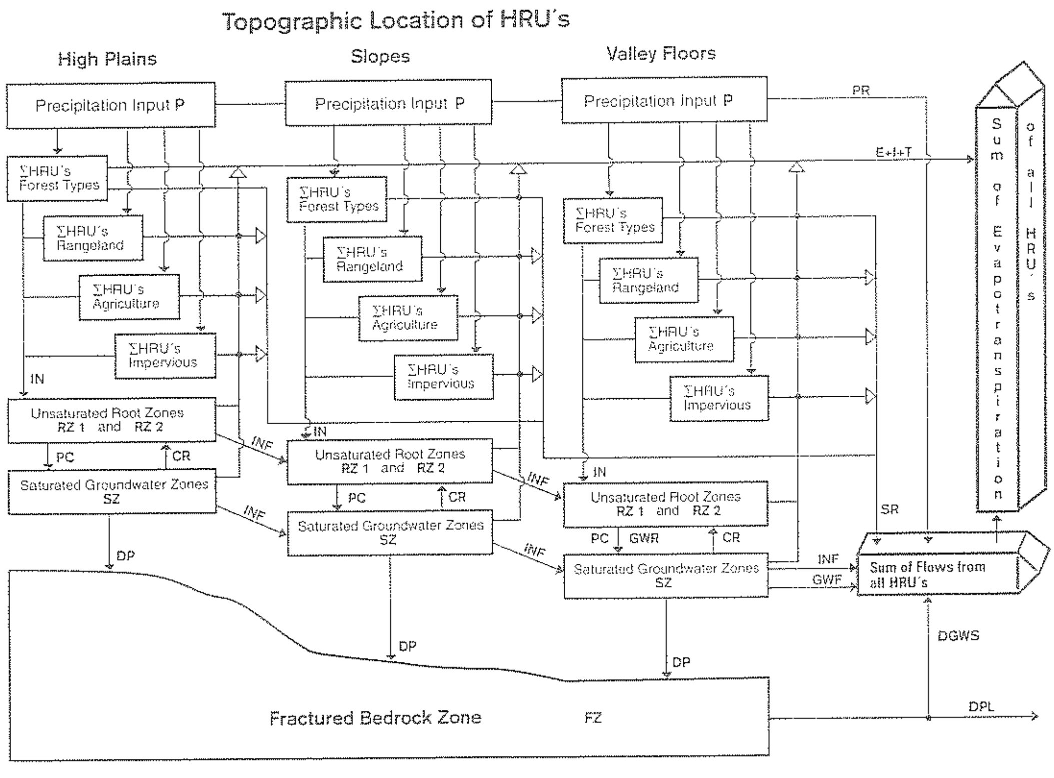

Fig. 2 Schematic topographical location of HRU's and water fluxes between them

slopes and the valley floor is shown in Fig. 2.

4.5 Model results

The fit between simulated and observed discharge for the twenty-year daily data set was always good as shown for the water year 1985 in Fig. 3. For the complete data set a high correlation coefficient of $r = 0.91$ was calculated. PRMS/MMS tended to underestimate advective winter storm hydrographs and summer base flow during long dry weather periods. These underpredictions may be caused by the use of non corrected rainfall data and seepage from the fractured bedrock zone into the river channel not accounted for in the model.

Sensitivity analysis revealed that the model was especially sensitive to the parameterization of the unsaturated root zone. These parameters are directly related to the vegetation cover and reflect the importance of the land-use heterogeneity in the basin model.

5. CONCLUSIONS and FUTURE RESEARCH NEEDS

The HRU-concept is a useful tool for regional hydrological modelling where spatial upscaling and downscaling of basin entities is required. If based on a thorough hydrological systems analysis the GIS-method used for their delineation is also applicable in basins of different climate and topography.

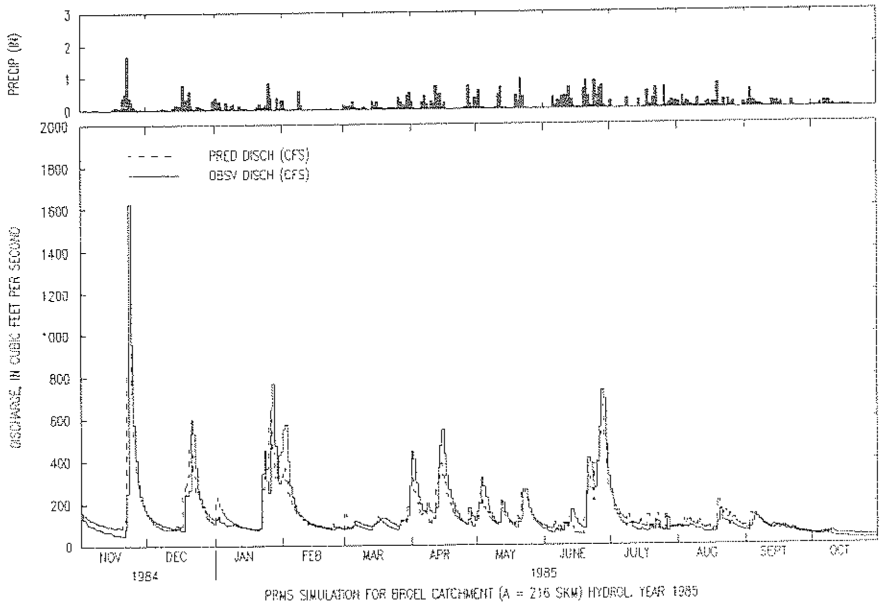

Fig. 3 Observed and simulated flow of the River Bröl during the hydrological year 1985

From the results presented the following future research needs can be identified: (i) for large-scale basins satellite imagery must be linked with the GIS-analysis; (ii) the distribution of precipitation in time and space must be incorporated into the delineation of HRU's; (iii) hydrodynamic discharge hydrograph routing is needed in larger catchments and new modules must be developed to improve the existing PRMS/MMS model; (iv) the MMS/PRMS model must be improved towards a object orientated design using a appropriate command tool language; and (v) the linkage between the different HRU's must be improved to cope for hydrodynamical modelling of water fluxes between them.

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