Application of GIS to derive Hydrological Response Units for hydrological modelling in the Bröl catchment, Germany

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Abstract GIS analysis is used to delineate Hydrological Response Units (HRUs) in the catchment of the River Bröl, Germany. The basics of the modified concept are discussed. The method is based on a thorough hydrological systems analysis, and HRUs are delineated by GIS analysis using the distributed basin’s physiographic properties: topography, soils, geology, rainfall and land use. The HRUs are applied as model entities in the Bröl basin (216 km²), Rheinisches Schiefergebirge, Germany, using the PRMS/MMS hydrological basin model. By using different GIS data layers altogether 23 different HRUs were delineating from classified pedo-topo-geological associations underlying four dominant land use classes. A hydrometeorological data time series consisting of 20 years of daily data was available for the validation exercise. The HRU model entities were parameterized as such that they contributed their surplus water not used for evapotranspiration to a common conceptual subsurface storage, drained by interflow to a groundwater storage in the valley floor which in turn drained to the channel network. The PRMS/MMS model simulated the observed daily discharge for the 20-year data set very well \((r = 0.91)\), and the model was sensitive to parameters directly related to the land use. Future research will focus on the spatial distributed precipitation for HRU-classification, and on the hydrodynamic routing of the modelled discharge.

INTRODUCTION

During the last decades hydrologists have focused their attention on the processes comprising a river basin’s hydrological dynamics and runoff generation (Hewlett & Hibbert, 1963). The latter is controlled by various physiographic basin characteristics, such as precipitation, topography, soils, geology and land use which are heterogeneously distributed within the basin. They are also controlling infiltration, surface runoff and evapotranspiration (Anderson & Burt, 1978; Beven & Kirkby, 1979), and therefore they are subject for 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 hydrological cycle and discharge output.

Models have to account for this heterogeneity if they claim to simulate the physical processes realistically. They therefore have to use physical laws or established empirical relationships from field studies (Flügel, 1979), and must be modularly structured to account for module development for various hydrological dynamics in different climatic environments.

The PRMS/MMS model developed by the US Geological Survey (Leavesley et al., 1983) used in this study fulfils these two conditions. Recent research work also includes the techniques of GIS into hydrological modelling (Moore, 1993; Maidment, 1991) providing a set of tools for modelling heterogeneous structured drainage basins (Flügel & Lüllwitz, 1993).

OBJECTIVES

The objectives of the study, which is part of a long term systems analysis of the Sieg drainage basin were four-folded: (a) to further develop the concept of HRUs using the test basin of the River Bröl; (b) to present the method of GIS analysis to delineate HRUs based on the hydrological systems analysis; (c) to use the HRUs in PRMS/MMS to simulate the hydrology of the Bröl basin for a 20-year data set; and (d) to identify further research needs to improve the modelling strategy presented.

BASIN HETEROGENEITY AND HRU CONCEPT

Understanding the processes interacting within the Soil-Vegetation-Atmosphere (SVAT) interface is of paramount importance, and a systems approach is essential if the hydrological dynamics of heterogeneously structured drainage basins should be analysed and modelled. Evapotranspiration, infiltration, surface runoff, interflow, groundwater recharge and runoff generation of the entire river basin are controlled by the SVAT-interface.

Figure 1 is showing the "real world" of a basin segment, and the interlinked water fluxes active within its topography. In terms of topography, soils, geology and land use the three-dimensional physiographic heterogeneity (Fig. 1) can be grouped together into different associations. Topography, soil types and geology are associated in soil catenas due to processes of weathering and erosion, and form pedo-topo-geological association. As a result, a gley soil will be found at the valley floor with shallow groundwater, but rarely on the plains, and certainly not on the slopes. General land use classes are agriculture, grassland, forest and impervious areas. They also show interdependencies with the soil catenas as agriculture prefers fertile, deep developed soils in the valley floor and on gentle hills, while grassland and forests are restricted to shallow, less productive soils on the slopes and on the plains.

Figure 1 clearly shows that each land use class is located on a specific pedo-topo-geological association forming a unique entity in the basin. The basic assumption of the HRU-concept is, that each of these entities also has unique hydrological dynamics due to their unique land use management and their common physical properties of the
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Fig. 1 Schematic presentation of basin subsystem storages and their interlinked water fluxes.
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"

This definition implies for each HRU, that the variation of the hydrological dynamics within it is negligible if compared with the difference to a neighbouring HRU.

RESULTS

Bröhl basin and database

The drainage basin of the River Bröhl (A = 216 km²) is a tributary of the River Sieg draining part of the Rheinische Schiefergebirge in Germany. It can be considered as representative for the larger drainage basin of the River Sieg (A = 2832 km²) which has an oceanic climate. Rainfall varies with elevation between 800 and 1200 mm. During summer, convective storms are frequent and in the winter half-year advective rainfall is dominant. The underlying 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.

Hydrological systems analysis

The drainage basin was intensively studied in various field campaigns and additionally the hydrometeorological database was analysed. From these studies the hydrological dynamics of the basin can be described as follows: (a) Surface runoff occurs only during extreme winter snow melt events occurring on frozen or saturated soil, or extreme summer storms with high rainfall intensities; (b) rainfall is intercepted by the forest and grassland vegetation, and the soil infiltration capacity can account for the throughfall; (c) the infiltrating water is stored in the pore volume of the unsaturated root zone for consumption by evapotranspiration; (d) if field capacity is exceeded, water percolates further downwards creating a wetted zone above the underlying impervious bedrock; (e) if coarse pores (earthworms, former root channels) are frequent, this slower percolation process is enhanced by the fast downwards flow of water from the surface towards this zone; (f) 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; (g) 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.

HRU delineation and linkage to the PRMS model

A comprehensive GIS database was built up by digitizing maps of soil types and land use, and by importing a DEM into the GIS. The HRUs were delineated by GIS analyses
as follows: (a) slopes and aspect were derived from the DEM; (b) topography soils and geology were grouped into the four different pedo-topo-geological associations of plains (0-10% slope and hydromorphic brown soils), slope I (10-20% and brown soils), slope 2 (> 20% and brown soils), the valley floor (> 0% and gley soil); (c) areal mean daily precipitation was calculated from Thiessen polygons and was applied uniformly to all HRUs; (d) four land use classes of forest (mixed deciduous and coniferous stands), rangeland, 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 database, 23 HRUs were delineated.

If linking the GIS analyses with the hydrological catchment model one must provide a conceptual interface between the data layers represented in the GIS database and the model modules simulating the different processes active within the various subsystems of the basin. This conceptual and systematic linkage is shown in Fig. 2 and can be done with the PRMS model incorporated into the MMS Modular Modelling System. The modular structure of MMS/PRMS guarantees that modules can be adapted to the real world or can be exchanged by others developed to simulate the physical processes active in a more appropriate way. As can be seen from Fig. 2, each process of the hydrological dynamics is simulated on the level of the GIS data layer and summarized for each heterogeneous HRU, therefore providing a real world distributing modelling.

Applying the HRUs in the PRMS/MMS model

The 23 HRUs delineated for the Bröl basin were tested with the hydrological basin model PRMS/MMS developed by the US Geological Survey (Leavesley et al., 1983; Flügel & Lüllwitz, 1993). Parameter optimization and sensitivity analysis was done using the 1980-1985 data and 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.

Model results

A 20-year hydrometeorological daily database with rainfall (six stations), temperature, radiation and discharge observations (each station) was available for the modelling exercise. The fit between simulated and observed discharge for the 20-year daily data set was always good as shown for the water year 1985 in Fig. 3. For the complete data set, the fit was described by a high correlation coefficient of \( r = 0.91 \). 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.
Fig. 2 Linking GIS data layers with various scales to the physically based, distributed hydrological river basin model PRMS/MMS.
CONCLUSIONS AND FUTURE RESEARCH NEEDS

The HRU-concept proved to be a useful tool in the River Bröl basin for regional hydrological modelling where spatial upscaling and downscaling of basin entities are 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. From the results presented the following future research needs can be identified: (a) for large-scale basins satellite imagery must be linked with the GIS analysis; (b) the distribution of precipitation in time and space must be incorporated into the delineation of HRUs; (c) hydrodynamic discharge hydrograph routing is needed in larger catchments and new modules must be developed to improve the existing PRMS/MMS model; (d) future development of this modelling approach must provide even tighter links between the database of the GIS and the model; (e) further hydrological model development must include object orientated concepts and parallel computing strategies.

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REFERENCES


