Using a distributed hydrologic model with the aid of GIS for comparative hydrological modelling of micro- and mesoscale catchments in the USA and in Germany

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Abstract The distributed, physical process model PRMS (Precipitation-Runoff-Modelling-System) was used to model the influence of land use on hydrological dynamics and to evaluate the performance of the model under different catchment conditions, scale and data bases. The subalpine microscale catchment of Deadhorse Creek ($A = 2.7 \text{ km}^2$), Rocky Mountains, Colorado, USA, and the mesoscale catchment of the River Bröl ($A = 216 \text{ km}^2$), in the middle mountain (Rheinisches Schiefergebirge), Germany, were selected for this comparative study. The following results can be summarized: (a) GIS classification techniques were successfully integrated and linked with the model and proved their tremendous potential for hydrological modelling in general, (b) PRMS also performed well under oceanic climatic conditions and varying slope classifications in the rangeland catchment of the River Bröl, and thereby demonstrated the reliability of the dynamic Hydrological Response Unit (HRU) concept. (c) The model was capable of simulating the effects of land use change, i.e. patchy clearcutting of timber, on streamflow generation in Deadhorse Creek by changing the classified HRUs within the model's structure.

INTRODUCTION

Numerous hydrological models have been developed for various applications. Computer simulation using such models is nowadays an essential tool for studying hydrological catchment dynamics. Extensive literature is available on this subject and no attempt is made here to give complete references. However among others, the work of Horton (1945), Penman (1948), Philips (1954), Richards et al. (1956), Nash (1957) and Kirkby (1978) surely mark some distinct steps in developing our conceptual and physical understanding of hydrological dynamics and approaches towards its modelling.

Models are either lumped, i.e. they use only spatial averages, or they are of a distributed type and allow for the spatial variability within a catchment. In the latter case the catchment is subdivided into different cells which are interactively linked in a cascade structure with each other to give the discharge from the catchment as the integrated result of the rainfall input. It is the structure of such cells and their interactive links which determines the degree of distribution.

About two decades ago the first Geographic Information System (GIS) was developed, providing software tools to analyse the spatially distributed, physiographic factors within a catchment influencing its hydrological dynamics. As such factors are essential components of a distributed hydrological model a close link to GIS technology
becomes a necessity if the hydrological catchment dynamics are to be simulated in a more realistic way (Maidment, 1991).

Often spatial distribution is represented by subdividing the catchment into subcatchments and such a differentiation is limited by the scale resolution of the topographical maps available. Such differentiation has no analytical, but merely a topographical base. The alternative approach towards incorporating spatial distribution is the analytical one introduced by Leavesley et al. (1983), by generating "Hydrological Response Units" (HRUs). As the physiographic factors represented in the physical model, like soil, geology, land use and topography are combined analytically for each HRU, this concept can make use of the full potential of spatial analysis offered by Geographic Information Systems.

OBJECTIVES

The purpose of this comparative study is to apply the Precipitation-Runoff-Modelling-System, PRMS, (Leavesley et al., 1983) in combination with the use of GIS spatial analysis techniques, both to a microscale forested subalpine catchment in the Colorado Rocky Mountain region, USA, and to a mesoscale middle mountain rangeland catchment within the Rheinisches Schiefergebirge, Germany. The modelling exercise had the following objectives: (a) to apply GIS techniques for catchment classification to identify the HRUs used as the spatial cell structure for PRMS. (b) to calibrate PRMS on a daily basis to both catchments having completely different physiographic conditions like land use, soils, geology, topography and climate; (c) to simulate the effects of patchy clearcutting on the hydrological dynamics of the subalpine forested catchment.

STUDY CATCHMENTS

The catchment of Deadhorse Creek is a microscale 2.7 km$^2$, subalpine catchment ranging in elevation from 2880 m to 3500 m. It is part of the Fraser Experimental Forest located in the Rocky Mountains west of Denver, Colorado, USA (Troendle & King, 1987). The climate is continental, having an average annual temperature of approximately 0.5°C. Annual precipitation varies between 432 mm and 711 mm, with an average of 584 mm. The soils within the catchment are Syrosems and Ranker soils, carrying spruce fir and Lodgepole pine forest. The historical data base ranges from 1976 till 1985.

The mesoscale catchment of the River Brôl ($A = 216$ km$^2$) is located within the Rheinische Schiefergebirge, Germany, about 50 km east of Bonn. The river drains into the River Sieg, which is a tributary of the River Rhine. The climate is oceanic with a mean annual temperature of 8°C. Annual precipitation ranges between 950 and 1300 mm giving an average of 1070 mm which falls mainly in summer and autumn. Soils consist of gleys on the valley floors, and brown soils as well as Lessivé soils on the hillslopes and upper peneplain. Land use is range land and forest of beech, oak, Lodgepole pine and spruce fir. The historical data base ranges from 1970 till 1989.
**PRECEPITATION-RUNOFF-MODELLING-SYSTEM (PRMS)**

The PRMS-model used in this analysis is a modular designed, deterministic, distributed, physical hydrological process model, which identifies the contributions of spatial distributed Hydrological Response Units (HRUs) within the catchment and aggregates their response to rainfall input as total runoff in the river channel. The model was developed by the US Geological Survey and is described in detail by Leavesley *et al.* (1983). Each major component of the hydrologic cycle is expressed by physical laws or empirical relationships using physical catchment characteristics. The PRMS structure has three major components: (a) the data management component ANNIE which handles the hydro-meteorologic input data base used by the model; (b) the PRMS library, consisting of both a source module and a load module, for the storage of the subroutines used to (i) simulate the physical process of the hydrologic cycle, and (ii) do the parameter optimisation and sensitivity analysis for model calibration and validation and (c) the output component which controls and handles model output.

Hydrological Response Units (HRUs) are the conceptual, analytical, distributed cell structures of PRMS and can be defined as follows: "Hydrological Response Units are regions scattered within a catchment having relatively homogeneous hydrological dynamics if compared with their neighbours due to their uniform type of land use, geology, soil, topography and rainfall". Partitioning the catchment into HRUs provides the ability to account for spatial and temporal variation of the basin's physical and climatic characteristics, and can thereby make efficient use of the powerful spatial analysis methods provided by GIS technology. Water and energy balances are calculated for each HRU separately, as shown in Fig. 1, and an areal weighted

![Fig. 1 Flow chart of the PRMS model input and output system (adapted from Leavesley *et al.*, 1983).](image-url)
summation of all the HRU responses is taken as the catchment’s response to rainfall input.

GIS APPLICATION

Two GIS software packages, ARC/INFO and SPANS, were used in the study and both performed well when establishing the HRUs used for the cell structure in PRMS (Lüllwitz, 1991). The capabilities of GIS software technology were used in the following ways: (a) to create a data base holding digitized information from various thematic maps; (b) to assign topological features and convert them into the Universal Mercator System (UTM) and Gaus-Krueger-Coordinates; (c) to carry out the combined spatial analysis of the distributed catchment features by using overlay procedures and contiguity measures to establish the different HRUs and (d) to present the different analysis steps and the HRU distribution in thematic maps (Fig. 2).

RESULTS

Spatial analysis of physiographic features by GIS linked with the structure of the hydrological model PRMS shown in Fig. 3 was done for both catchments. GIS analysis was supported by land use field mapping. Overlay techniques provided by the GIS played a major role in establishing the HRUs. PRMS is linked with the GIS analysis by incorporating HRUs together with a hydro-meteorological data base, and, after calibration, produces the hydrograph output from the catchment.
**GIS Analysis**

The establishment of HRUs defined above was the overall aim of the field mapping and GIS analysis carried out in both catchments. This analysis was based on the hydrological process dynamics within the two catchments as an integrated result of the catchment's physiographic properties, and was done in different steps described briefly as follows: (a) The different types of land use (forest, range land, roads, settlements) were mapped in the field and digitized together with topographic and thematic maps of soil types and geology. (b) From the topography different classes of slope degrees and aspects were derived by the GIS. (c) The various catchment features (topography, soil depth, soil heterogeneity, types of land use) previously digitized were sorted into representative classes according to their physical and hydrological properties. (d) All classified coverages were then transformed to the Universal Mercator System, UTM, and the Gauss Krueger System, and the different data sets of topography, land use, soils, slope degrees, aspect and land-use were successively overlaid to create new classified coverages as shown for Deadhorse Creek in Fig. 3. (e) Coverages were aggregated again, but those having less than 2% of the catchment area were added to the next neighbouring one. (f) After all coverages were analysed by overlay procedures the final HRUs were established. Each has a uniform class of land use, soil, slope gradient and aspect which makes them distinctly different from all other surrounding HRUs.
Model Application

Applying PRMS in both catchments using the historical data base included the following five modelling procedures: (a) Initialisation using the first two years of data. (b) Calibration carried out with another three years of historical data using two criteria (i) that simulated flow should match observed data, and (ii) selected model parameters should be consistent with the physiographic catchment properties. (c) Optimization of model parameters using specific routines within PRMS. (d) Validation of parameter settings using the following years of the data set. (e) Simulation without further parameter changes to evaluate the model's performance and sensitivity to land use changes in comparison with historical flow records.

All of these five steps have been successfully carried out in both micro- and mesoscale catchments and PRMS performed well (Fig. 4) giving evidence that the concept of classified HRUs established by GIS overlay analysis is applicable to subalpine and middle mountain catchments having quite different climate and land use conditions. Comparing the modelling results for both catchments, using the entire historical data, revealed that PRMS simulates hydrographs during high flow conditions better than during low flow in summer (Fig. 4). This either indicates an insufficient simulation of groundwater and interflow contribution, or calculated evapotranspiration is too high during summer.

Due to the differences between the two catchments described above the hydrologist must pay special care when generating the HRUs, considering the different types of soil and land-use during the various overlay procedures in the GIS. By analysing different HRUs it was found, for example in the Brôl catchment, that slope aspect is of less importance than slope gradient when comparing simulated flow with historical

![Fig. 4 Simulated and observed discharge, River Brôl 1977.](image)
data. It also seems that field capacity dominantly controls the generation of interflow and surface runoff, and this was also found by Flügel (1978) for a loess covered catchment in southern Germany.

The effect of changing land use, i.e. the clearcutting of timber, on streamflow was simulated successfully for Deadhorse Creek using the historical stream flow data set and considering post-treatment activities in the parameter settings. The calibrated model was first run on the entire climatic data set assuming a complete forest cover. Later changes were made in the HRU data set by adding another HRU to account for the clearcuts and the simulation was repeated using the same climatic data set as before. The simulation results shown in Fig. 5 indicate an earlier response of the catchment during snow melt after the clearcutting, and give evidence that the change of land use was sufficient to result in a corresponding change of the hydrological dynamics, which was correctly modeled by PRMS.

![Graph](image)

**Fig. 5** Observed discharges, Deadhorse Creek, 1982-1983 compared with a simulated discharge after adding HRU to account for clearcuts.

**CONCLUSIONS AND RECOMMENDATIONS**

From the comparative modelling study the following conclusions can be derived: (a) GIS spatial analysis can be linked successfully with PRMS by applying classification and overlay techniques to establish the Hydrological Response Units (HRUs) distributed cell structure. (b) HRUs are independent of the subcatchment structure, but the hydrologist must pay careful attention to existing physical interactions when combining catchment properties such as soil types and land use in HRUs. (c) In the mesoscale catchment of the River Bröl slope aspect was found to be of less importance to flow...
generation than slope gradient. (d) PRMS proved to be reliable when simulating the hydrological dynamics of both (i) the microscale, subalpine, forested, continental catchment of Deadhorse Creek, and (ii) the partly forested, mesoscale, rangeland catchment of the River Bröl in the oceanic middle mountains. (e) By comparing simulated and historical flow data it was found that PRMS models hydrographs better for high flow than for low flow periods. (f) PRMS is able to simulate timber clearcutting and the resulting increase in water yield by changing the number and area of the HRUs and is therefore a useful tool for modelling the influence of land-use changes within a catchment on its hydrological dynamics.

The conceptual use of HRUs as a spatial distributed cell structure is a different approach towards modelling hydrological catchment dynamics compared with the commonly used catchment partitioning into subcatchments identified by topographic means. Further recommendations to improve the model performance are to (a) extend the numbers of HRUs from the present 25, (b) include a more flexible spatial distribution of rainfall input and evapotranspiration, and (c) to improve the modelling of groundwater and interflow contribution during low flow periods.

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