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Breaking up is always difficult – landscape discretization as a process-transfer approach for prediction in ungauged basins

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Abstract Predictions of hydrological variables in ungauged basins (e.g. evapotranspiration or runoff values), necessitates understanding of the first order process controls driving these variables. This knowledge is usually transferred from other nearby smaller experimental test basins and upscaling is typically required. Nevertheless, simple black box models do not capture first order process controls. In this paper we describe a new process-transfer approach whereby delineation and characterization of similar landscape elements is used to aid identification of first order controls on water flux in time and space. We argue that this spatial delineation can serve as the basis for a process-oriented distributed model to perform more reliable and "process-realistic" predictions in the ungauged basin. Thereafter, suitable models/-modules can be applied to each landscape unit separately. We highlight this strategy using case studies in two mountain basins in the Southern Black Forest Mountains, Germany, and the Cascade Mountain Range, Oregon, USA. Here the characteristics of the soil and drift covers and the topography served as main criteria to identify units with the same dominating runoff generation processes. The delineation method is based on previous experimental investigations including tracer studies.

Key words hydrotopes; process-based predictions; regionalization

INTRODUCTION

The last two decades have witnessed considerable advances in understanding runoff generation processes in gauged headwater basins (see reviews Anderson & Burt, 1990; Bonell, 1998). We now have solid conceptual and physical understanding of hydrological processes at the hillslope and headwater scale (e.g. Mosley, 1982; McDonnell, 1990; Hinton *et al*., 1994; Montgomery *et al.* 1997; Rice & Hornberger, 1998; Sidle *et al*., 2000, 2001; Burns *et al*., 2001; McGlynn *et al*., 2002). Recently, work has begun to explore how the dominant runoff generation processes identified at headwater scales applies to larger basins (1(0)–100(0) km^2) (e.g. Hoeg *et al*., 2000; Uhlenbrook *et al*., 2002). Nevertheless, it is still difficult to estimate the dominant runoff generation processes in a catchment (regardless of size) without experimental investigations and gauged data. This is mainly due to two reasons: (i) The complexity and temporal and spatial variability of the runoff processes; (ii) our lack of tools to transfer process understanding to ungauged basins.

This paper advocates a new process-transfer approach whereby process knowledge (for example runoff generation processes or hydrograph components) can be transferred via mappable hydrogeomorphic units. By delineating and characterizing similar landscape elements (often called hydrotopes or hydrological response units (HRU), e.g. Flügel, 1995, 1996; Leavesley & Stannard, 1995), units with the same dominating runoff generation processes can be incorporated into a process-oriented distributed or semi-distributed rainfall–runoff model. This will enhance model performance and "process-realistic" runoff calculations. When compared to using an arbitrary spatial model discretization, this approach can be much more effective (e.g. Scherrer & Naef, 2001; Uhlenbrook & Leibundgut, 2002). It can also be used for better environmental planning, for instance for an improved land use or decentralized floodwater management.

This paper discusses the power of a landscape discretization approach to transfer knowledge and suitable models/modules to ungauged basins. We argue that it is possible to preserve the three-dimensional (3-D) heterogeneity of real world catchments to a large extent in a model, by capturing the main hydrological components through a process-oriented landscape discretization.

TEST SITES

The study was performed in two large watersheds: the 40 km^2 Brugga basin in the Black Forest Mountains, southwest Germany and the 62 km^2 HJ Andrews Experimental Forest basin (Western Cascade Mountains, Oregon, USA). Both are mountainous catchments with an elevation range of more than 1000 m (Table 1) that contain several gauged sub-basins. The bedrock at the Brugga consists of gneiss and is covered by a glacial and periglacial drift cover with varying depths (0–10 m). Brown soils have mainly developed in the drift cover material. The geology at the HJ Andrews is composed partly by hydrothermally altered volcanoclastic rocks, ash flows and basaltic andesite lava flows. The morphology of both basins is dominated by moderate to steep slopes (approximately 75% of the basin area), hilltops, relatively flat hilly uplands, and predominantly narrow valley floors. Somewhat wider valley floors with porous groundwater systems can be found in glacially-scoured U-shaped valleys. The overall average slope is about 19° and 20° for the Brugga and HJ Andrews basin, calculated with a 50 × 50 m^2 and 10 × 10 m^2 digital elevation model (DEM), respectively. Forest cover is dominant at both sites (Table 1), but about 23% is used as pasture land at the Brugga. Further details for the Brugga can be found at Uhlenbrook & Leibundgut (2002) and Uhlenbrook *et al*. (2002), and of the HJ Andrews by Swanson & James (1975), Jones & Grant (1996), Jones (2000) and Swanson & Jones (2001).

Despite the many similar physiographic characteristics at both sites, there are many differences that influence the hydrological response significantly: (i) the rainfall at the Brugga is distributed more or less equally during the year, with a little maximum during early winter. This causes a nival runoff regime with a maximum during late winter/early spring due to snow accumulation and snowmelt. The summer is extremely

Table 1 Comparison of the major basin characteristics of the two test sites: Brugga basin (Black Forest Mountains, southwest Germany), and the HJ Andrews basin (Western Cascade Mountains, Oregon, USA).

	Brugga Basin	HJ Andrews Basin
Area	40 km^2	62 km^2
Elevation range	438–1493 m a.s.l.	427–1646 m a.s.l.
Mean Slope	19°	20°
Geology	Metamorphic rocks (Paleozoic)	Tuff, breccias, basalt, andesite (tertiary)
Soils types	Quaternary deposits, brown soils	Quaternary deposits, brown soils, loose
Land use	Forest (75%), pasture land (22%) and urban (3%)	Forest (100%), partly clear-cut
Water balance:		
Precipitation	1780 mm $year^{-1}$	2300 mm $year^{-1}$
Discharge	1230 mm $year^{-1}$	1400 mm $year^{-1}$
Evapotranspiration	550 mm $year^{-1}$	900 mm $year^{-1}$

dry at the HJ Andrews and more than 80% of the precipitation falls between October and April. The snow also causes a nival runoff regime that is more pronounced than in the Brugga. (ii) The bedrock is more acidic at the Brugga, with orthogneiss and granite as predominant rocks, while at the HJ Andrews, andesites and basalts have higher acid neutralizing capacity. This causes finer loamy soils and deeper weathering with large porosity in the upper soil at the HJ Andrews. Earthflow and landslide susceptibility at the HJ Andrews is much higher, and many earthflows (stabilized and active) with a depth of several tens of metres are known and mapped. (iii) The forests (mainly spruce) at the Brugga have a more or less uniform age of about 80 years. At the HJ Andrews clear cuts (and re-plantation) were performed at several parts during the last decades. A large percentage is still covered by old-growth conifer forest (approx. 150–450 years old).

DELINEATING UNITS WITH THE SAME DOMINATING RUNOFF GENERATION PROCESSES: AN EXAMPLE FROM ONE BASIN

Hydrologically homogenous regions were determined within a GIS environment for the Brugga and the larger surrounding Dreisam basin (Fig. 1) using generally available data sets (details are given at Tilch *et al.*, 2002). A similar delineation for the HJ Andrews basin is in progress to extend model testing and to develop catchment comparisons. First, areas with predominant surface runoff production were delineated: urban areas, bedrock outcrops (Horton overland flow), water bodies (direct channel interception) and saturated areas (saturation overland flow). Then, areas that are not flood runoff generation sites (base flow recharge areas) were delineated. These were predominantly flat areas at the upper parts of the basin or consolidated moraines, which have a relatively large storage. The remaining areas, valley floors and moderate to steep hillslopes were differentiated by the structure and the lithology of periglacial drift covers. We rationalized that steep slopes with a very coarse soil cover would produce very quick lateral preferential macropore flow. Tracer investigations at these

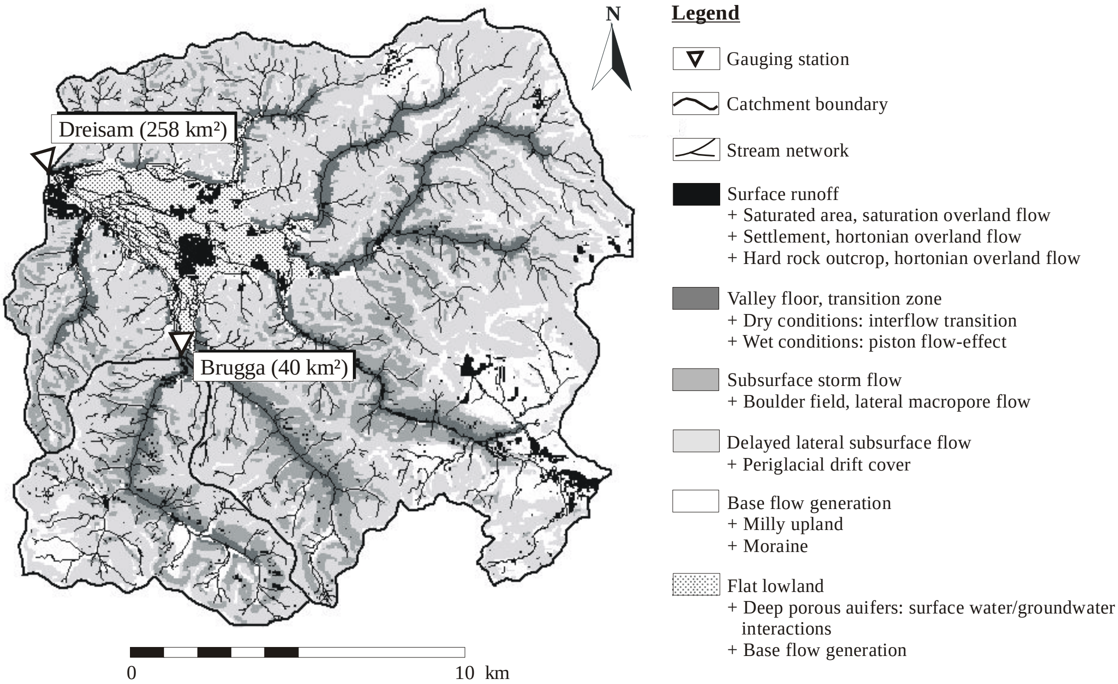

Fig. 1 Landscape units with the same dominating runoff generation processes (described in the legend) at Dreisam basin (Black Forest Mountains, south-west Germany). The highly investigated sub-basin Brugga is located in the southwest.

sites showed flow velocities of several tens of metres per hour (Mehlhorn *et al.*, 1998). Moderate steep slopes have a stratified drift cover and show a more delayed response (Uhlenbrook *et al.*, 2002). The narrow valley floors of the deeply incised, mountainous streams serve mainly as transition zones for hillslope water. In the larger Dreisam basin another morphological unit—the flatter low lands with deep porous aquifers—come into play. In these areas, near stream surface water–groundwater interactions are important. At areas that are not near the stream, infiltrating rainwater percolates down to the porous aquifer.

INCORPORATING PROCESS KNOWLEDGE INTO A PROCESS-BASED MODEL

We spatially delineated the catchment into similar runoff generation units and used these within our process-oriented model. The semi-distributed TAC model (tracer aided catchment model; see Uhlenbrook & Leibundgut, 2002) was developed to compute the water balance on a daily mode. For each of the units (see Fig. 1) a specific runoff generation routine was developed, using linear and nonlinear storage routines. The other model modules, i.e. the snow and soil module, were adopted from the HBV model (Bergström 1992). The spatial variability of basin precipitation was considered using a nonlinear elevation gradient for 11 elevation zones (100 m intervals). This gradient was kept constant within the basin, but varied for every modelling time step. The TAC model was applied using daily values with good success. In particular, the use of tracer data, i.e. contribution of the different runoff components and the concentration of dissolved silica, showed that not only the total runoff was computed well, but also the internal processes were modelled correctly (Uhlenbrook & Leibundgut, 2002).

TAC was then modified to link better with the landscape discretization information in the form of the TAC^D model ("^{D}" for distributed; details are given by Uhlenbrook *et al.*, 2004) with the following modifications: (i) It is still a conceptual model with a modular model structure using storage routines to conceptualize the runoff generation processes, but it was changed from semi-distributed to a fully distributed raster model. The spatial discretization is based on the spatial delineation of the units with the same dominating runoff generation processes, which were converted into 50 × 50 m^2 raster cells that are connected by a single flow algorithm. The distributed computation allowed a realistic representation of lateral flows at the hillslopes (Fig. 2). It can be attributeed as a 2.5-D model structure, as the vertical flows are conceptualized by boxes at

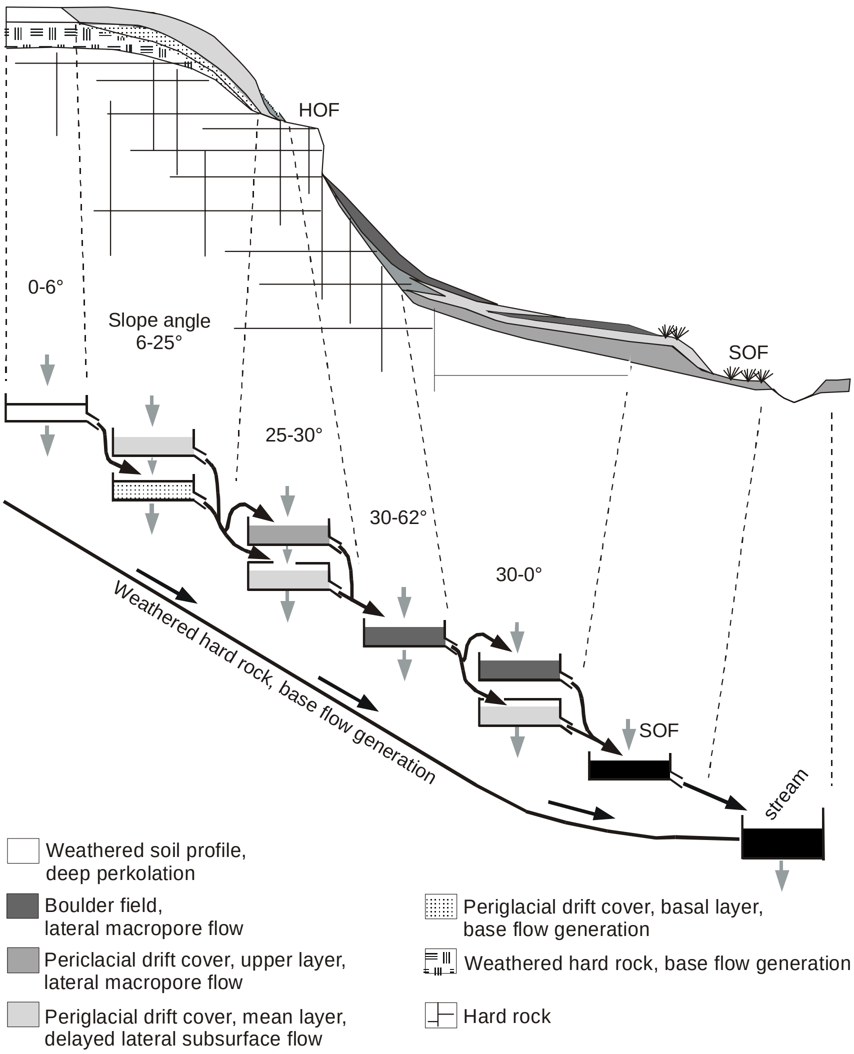

Fig. 2 Schematic hillslope and conceptualization of runoff generation processes by distributed and interlinked boxes within the TAC^D model. HOF: Horton overland flow. SOF: Saturation overland flow.

several depths that are connected horizontally by a 2-D scheme. In addition, the distributed version of the model enabled the use of spatially and temporally variable input data (i.e. meteorological variables), and in particular rainfall radar data (Uhlenbrook & Tetzlaff, 2005). (ii) The aim of the model was not only to simulate the annual water balance and the daily contributions of different runoff components correctly, but in addition, floods and their generation processes should be simulated correctly. Therefore the modelling time step was reduced to an hourly mode. (iii) Channel routing is modelled with a kinematic wave approach (implicitly, nonlinear). In this module the modelling time step was reduced to 60 seconds for numerical reasons.

To compute the potential evapotranspiration the approach of Penman & Monteith was used. Therefore, 16 different land use classes were parameterized and the required meteorological input data were regionalized. The slope, aspect and possible shadowing of every single raster cell were considered using the model POTRAD (van Dam, 2000) to estimate radiation.

HOW THIS WORK APPLIES TO UNGAUGED BASINS

In the Brugga example, good modelling results were obtained with only a limited calibration of the model to observed runoff data. In addition, the use of tracer data helped to test the model performance, and demonstrated that not only was the total discharge modelled correctly, but also that the distribution of different runoff components was modelled well. We acknowledge that this test used flow and input data for calibration, which is typically not available in ungauged basin problems. Notwithstanding, good results were also obtained for neighbouring basins and the surrounding Dreisam basin, without intense parameter adjustment. Here the same landscape discretization was performed and the respective module and parameters were transferred directly. This indicates the suitability of the model for performing predictions in ungauged basins, which are characterized by similar physiographic characteristics. In many ungauged basins and many parts of the world, land use, geology, soils and topographic information are available. We propose that this information may be highly valuable for modelling purposes whereby delineated catchment units, guided by “expert knowledge” of dominant runoff generating processes, may be a way to perform hydrological predictions that are based on dominating physical processes. This work is currently being extended to the H.J. Andrews as an additional test case, where as in the Brugga case, it can be applied to an adjacent basin for validation.

CONCLUDING REMARKS

– The delineation of similar landscape elements can be a useful process transfer tool for defining dominant runoff generation processes in ungauged basins.
– Based on such spatial delineations, suitable modules and parameters sets can be transferred directly for uncalibrated model runs.
– The delineation procedure offers an opportunity to preserve to a large extent the 3-D heterogeneity of a real-world catchment where 2-D delineations and the third

dimension including the lateral connectivity of the landscape elements are considered.

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