

Regionalization of geomorphometric parameters in hydrological modelling using GIS

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Abstract One major research interest of the DFG research project Regionalization in Hydrology is the problem of spatial parameter relationships relevant for hydrological modelling. In this study, physically based hydrological models and Geo-Information Systems (GIS) have been applied to investigate relationships between geomorphometry and hydrological processes at different spatial scales. The results show the importance of geomorphometry through (a) high correlations of different geomorphometric parameters with hydrograph indices, (b) the relevance of soil-geomorphometry relationships for parameterization in hydrological modelling, and (c) the correspondence of mesoscale landform types to areas showing similarity in runoff production. Scale thresholds related to catchment sizes are proposed.

INTRODUCTION

During recent decades, a growing number of environmental science disciplines have used hydrological models in planning and resource management, e.g. for flood forecasting (Penning-Rowsell, 1994). There has been a focus on simplification of model structure and parameter demand, so that models are usable at larger spatial scales with lower parameter requirements. Whereas hydrological processes at the microscale are well understood and appropriate models have been developed, difficulties result from applying microscale equations to meso- or macroscales (e.g. grid cells of tens of metres in a distributed model). This leads to the necessity for *regionalization* of model equations and/or parameters (Kleeberg, 1992).

Geomorphometric parameters, such as slope angle and slope length, or locations of topographic divergence and convergence are the main controls in a number of hydrological processes. Attempts to quantify this influence show that geomorphometric parameters controlling runoff at the microscale do not necessarily have the same influence at larger scales.

This study is focused on the influence of geomorphometry on runoff processes. The main aim is to identify geomorphometric parameters which significantly influence hydrological processes at different scales and to look for regionalization techniques to transfer parameters from one scale to another (Sivapalan & Kalma, 1995). Therefore, the first step is to determine thresholds in catchment size, where the significance of one geomorphometric parameter declines, and then to identify new or changed parameters

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appropriate at the new scale, e.g. larger catchment size (Kirkby, 1988). These parameters are called "effective parameters" as they effect hydrological processes significantly.

This study has been carried out within the framework of the Schwerpunktprogramm "Regionalization in Hydrology" of the Deutsche Forschungsgemeinschaft, in which various German research groups have addressed the question of regionalization of hydrological models and parameters. Study areas include the Weiherbach catchment (6.3 km²) in the Kraichgau area, southwest Germany, and the Leineturm catchment (991 km²) in central Germany, which is a part of the Weser catchment. The Digital Elevation Models (DEMs) used have grid resolutions of 12.5 m and 31 m, respectively.

METHODOLOGY

Geomorphometric parameterization and classification using GIS

The study is concerned with determining the influence of geomorphometric features on hydrological processes at different scales, using and testing GIS technologies. ARC/INFO[®] and GRASS were used as basic GIS-packages in the entire research project. Additionally, geomorphometric software packages were included in our investigation, e.g. DGRM (Dikau, 1992). One research task was the analysis of the GIS packages concerning their capabilities in geomorphometric modelling and the development of new geomorphometric tools. Therefore, a hierarchical framework classifying existing and new GIS tools was developed (Schmidt & Dikau, 1999). It consists of a classification of geomorphometric objects, parameters and methods, in which primary geomorphometric parameters (e.g. local slope angle) and representative geomorphometric parameters (e.g. hypsometric integral) are identified (Fig. 1). This approach was used to prepare an inventory of GIS tools for deriving geomorphometric objects and parameters from raster-based DEMs using GIS. Table 1 shows some examples of representative geomorphometric parameters for catchments used in this study.

Hydrological models

In order to take varying catchment sizes and modelling concepts into consideration, two hydrological models have been used.

The hydrological model TOPMODEL (Beven & Kirkby, 1979) is based on the concept of variable contributing source areas for streamflow generation. The tendency of any point (in this case, one pixel) in a catchment to generate saturation excess overland flow and thus to contribute to streamflow generation is given by its topographic wetness index $\ln(a/\tan\beta)$, where a is the area drained per unit contour length and β is the slope angle at this point. Model inputs are the frequency distribution of the topographic wetness index $\ln(a/\tan\beta)$, precipitation and evapotranspiration data. Further input parameters describe catchment behaviour concerning storage, channel routing and root zone conditions. Model output is the runoff hydrograph for the catchment, the water balance and saturated contributing areas for each time step. Figure 2 shows a calculated and an observed hydrograph for the Leineturm catchment.

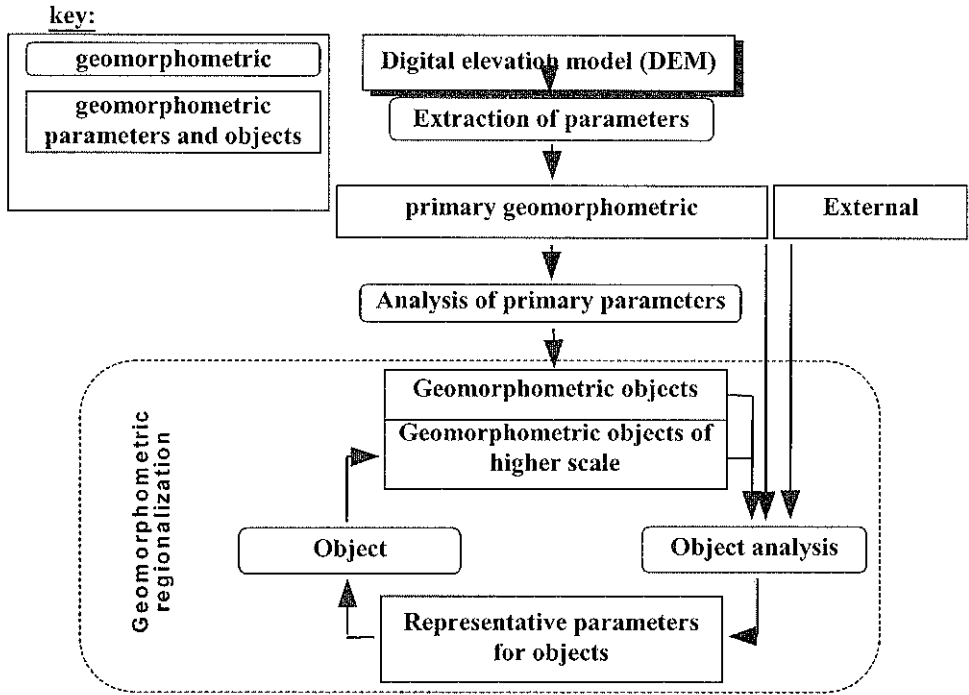


Fig. 1 System of methods for the extraction of geomorphometric parameters and objects. The system is based on the extraction of *primary geomorphometric parameters*. In a second step these parameters are analysed to derive *geomorphometric objects*. These objects are the basis of a hierarchical system consisting of object analysis and object aggregation leading to *representative geomorphometric parameters* and *geomorphometric objects of higher scale*.

The topographic wetness index $\ln(a/\tan\beta)$ is generally derived from a DEM. Thus, it is important to be aware of the close dependency between the model output and the grid size of the DEM used. Zhang & Montgomery (1994) stated that a 10 m grid size seems to be appropriate for deriving the topographic wetness index $\ln(a/\tan\beta)$ for TOPMODEL. However, Wolock & Price (1994) discussed the effects of digital elevation model map scale and data resolution on the distribution of the topographic

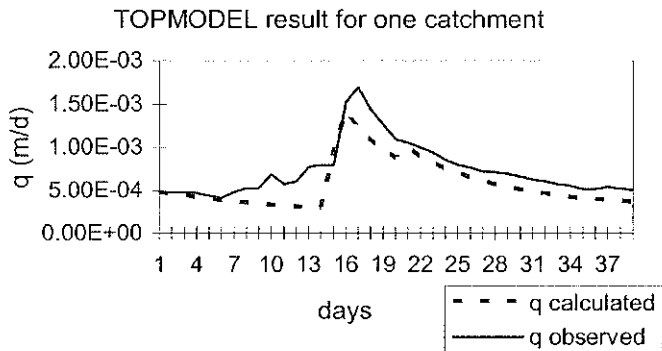


Fig. 2 Calculated and observed hydrographs for the Leineturm catchment.

Table 1 Some examples of geomorphometric catchment parameters derived by GIS-methods.

| Drainage basin parameters | GIS-function/module | GIS/program |
|---|---------------------------|-----------------------------|
| Average height of catchment H_A | r.statistics / ZONALSTATS | GRASS/ARC/INFO [®] |
| Relief (maximum height difference) dH_E | r.statistics / ZONALSTATS | GRASS/ARC/INFO [®] |
| Relief ratio (= relief/length) dH_R | r.mapcalc / arithm. calc. | GRASS/ARC/INFO [®] |
| Height distance outlet – average height dH_M | r.statistics / ZONALSTATS | GRASS/ARC/INFO [®] |
| Relief magnitude index (= $dH_M/\sqrt{\text{area}}$) I_M | r.mapcalc / arithm. calc. | GRASS/ARC/INFO [®] |
| Hypsometric integral I | r.statistics | GRASS |
| Skewness of hypsometric curve SK_H | r.statistics | GRASS |
| Catchment volume V_E | r.statistics / ZONALSTATS | GRASS/ARC/INFO [®] |
| Average catchment slope S_B | r.statistics / ZONALSTATS | GRASS/ARC/INFO [®] |
| Maximum catchment slope S_M | r.statistics / ZONALSTATS | GRASS/ARC/INFO [®] |
| Median catchment slope S_{Me} | r.statistics / ZONALSTATS | GRASS/ARC/INFO [®] |
| Catchment area with low slope angles A_{LS} | r.statistics / ZONALSTATS | GRASS/ARC/INFO [®] |
| Catchment area with high slope angles A_{HS} | r.statistics / ZONALSTATS | GRASS/ARC/INFO [®] |
| Median profile curvature $C_{V_{Me}}$ | r.statistics / ZONALSTATS | GRASS/ARC/INFO [®] |
| Median plan curvature Ch_{Me} | r.statistics / ZONALSTATS | GRASS/ARC/INFO [®] |
| Catchment area with low profile curvature A_{C_p} | r.statistics / ZONALSTATS | GRASS/ARC/INFO [®] |
| Catchment area with low plan curvature A_{C_h} | r.statistics / ZONALSTATS | GRASS/ARC/INFO [®] |
| Maximum flow length Fl_{MAX} | FLOWLENGTH | ARC/INFO [®] |
| Average flow length Fl_M | FLOWLENGTH | ARC/INFO [®] |
| Average slope of longest flow path S_{Fl} | FLOWLENGTH | ARC/INFO [®] |
| Average of topography – index λ | r.statistics / ZONALSTATS | GRASS/ARC/INFO [®] |
| Standard deviation of topography – index σ | r.statistics / ZONALSTATS | GRASS/ARC/INFO [®] |

index, concluding that there is an interdependence between DEM scale and grid resolution. This means, that the optimal grid size also depends on the DEM map scale. For this research, a 31 m grid was chosen. It might be too fine for the whole catchment (991 km²) and too coarse for very small-scale catchments, but for most of the investigated areas it is an appropriate compromise. By way of comparison, Zhang & Montgomery (1994) worked in catchments of 0.3 km² and 1.2 km².

The three-dimensional model SAKE (Simulationsmodell für Abflüsse Kleiner Einzugsgebiete, runoff simulation model for small catchments) works with a regular horizontal grid and an uneven vertical discretization. The different hydrological processes are modelled by separate modules (Merz & Bárdossy, 1998) for infiltration, macro-/micropore flow, unsaturated flow, overland flow and channel flow. The physical basis of the process modelling is provided by the Richards equation (vertical soil water movement), kinematic wave approximation (macropore flow) and diffusion wave model (overland flow). Calibration and validation have been carried out in a highly instrumented subcatchment of the Weiherbach (Merz & Bárdossy, 1998). The SAKE model outputs detailed hydrological event information: runoff hydrograph, soil moisture, interception, overland flow, macropore moisture.

Relevance of geomorphometric parameters and classifications in hydrological modelling

This approach is based on the application of the geomorphometric and hydrological models described above to different subcatchments of both study areas. In order to

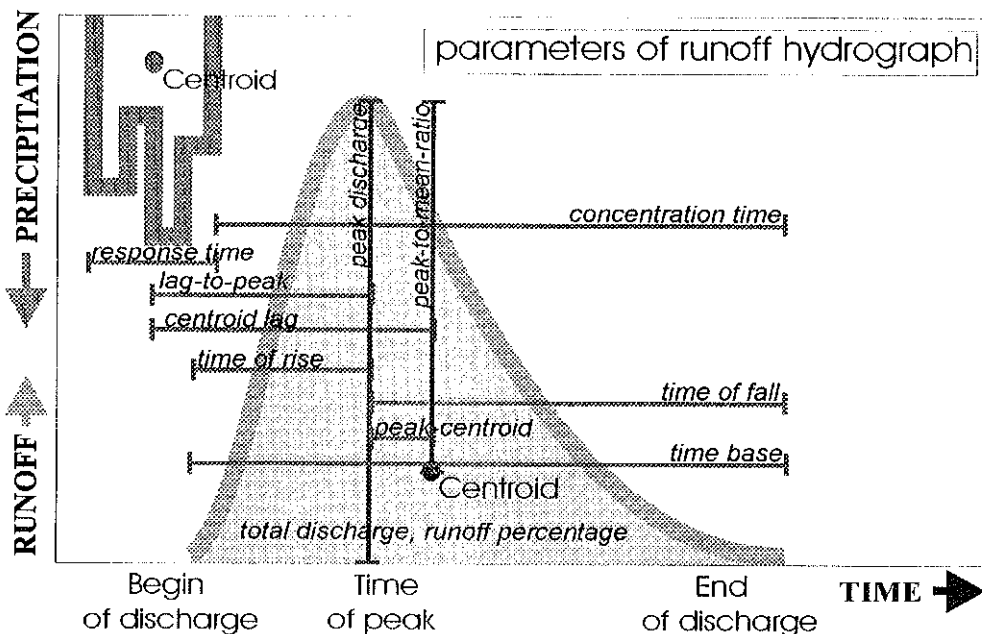


Fig. 3 Hydrological parameters derived from TOPMODEL and SAKE hydrographs.

derive relationships between catchment geomorphometry and hydrological response, most model runs were carried out using constant homogeneous soil and vegetation conditions. The simulated hydrograph was used to calculate a series of runoff indices (Fig. 3). Several statistical techniques and sensitivity studies were used to analyse the model output with respect to geomorphometric parameters over different spatial scales.

Flow depths produced by the SAKE model were used to assess geomorphometric effects on runoff production at the local scale. Primary geomorphometric parameters were correlated with flow depth for catchment areas with high runoff contribution (multiple regression, discriminant analysis). Furthermore, the relevance of soil-geomorphometry relationships in runoff production at small catchment scales was tested through sensitivity analysis using the SAKE model (Schmidt *et al.*, 1999).

To derive geomorphometric parameters with hydrological relevance at the catchment scale (i.e. effective geomorphometric parameters), statistical analyses of representative geomorphometric parameters and hydrological indices (Fig. 4) were carried out. Therefore, subcatchments of several size orders were identified. Each subcatchment has a characteristic set of geomorphometric parameters and hydrological indices. Thus, runoff indices were clustered in groups of regions with similar hydrological characteristics. These clusters were analysed to identify the best explanatory geomorphometric parameters using a combination of several statistical functions.

Another approach was the classification of the entire catchment based on a geomorphometric model described by Dikau (1994) and Dikau *et al.* (1995), resulting in mesoscale landform units. These units were used to test hydrological clusters (Fig. 5).

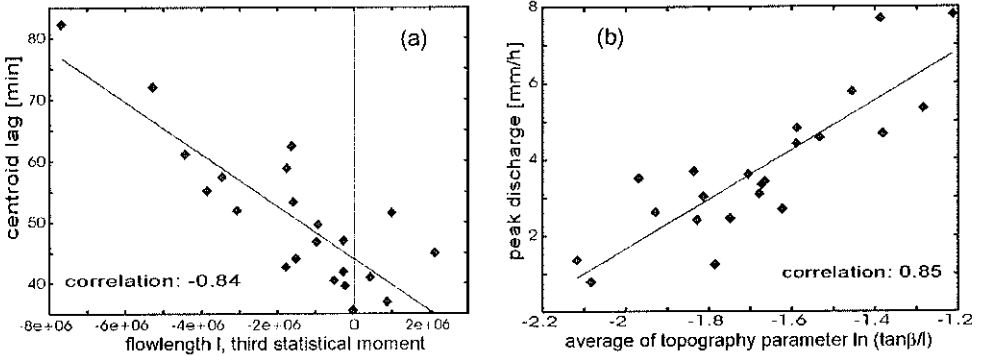


Fig. 4 Regression analysis of topographic parameters and hydrological indices in the Weiherbach catchment: (a) flow length and (b) topographic parameter $\ln(\tan\beta/l)$ show high correlation coefficients.

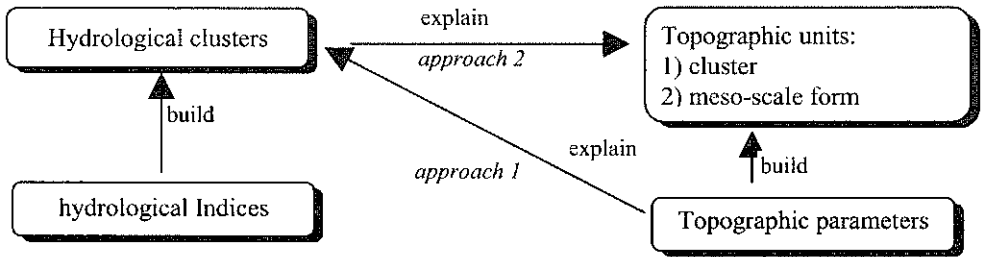


Fig. 5 Two approaches used for quantifying the relationships between geomorphometry and hydrological conditions.

Scale dependencies of hydrological properties and representative geomorphometric parameters

The analysis of the behaviour of hydrological properties and geomorphometric parameters on different scales is necessary to determine thresholds in area scale and scale dependency of significant parameters. Scatterplots of hydrological properties and geomorphometric parameters, against catchment size, show the scale dependencies of a number of properties and their variability (Wood, 1995). They give a first idea of scale thresholds (Fig. 6).

Another approach determining the changing significance of geomorphometry on hydrological processes for increasing catchment sizes is to correlate representative geomorphometric parameters with hydrological indices in defined catchment size classes (Table 2). The moving window calculation with two parameters: (a) the hydrological index “total discharge”, and (b) the average of the topographic wetness index $\ln(a/\tan\beta)$, distinguishes between four catchment classes: 0–10 km², 10–20 km², 20–40 km² and >40 km². For catchments larger than 40–50 km² the variances are close to 0, which might indicate a decreasing significance of these parameters at higher scales. High values at the end of the scale reflect few data in this value range (Fig. 6).

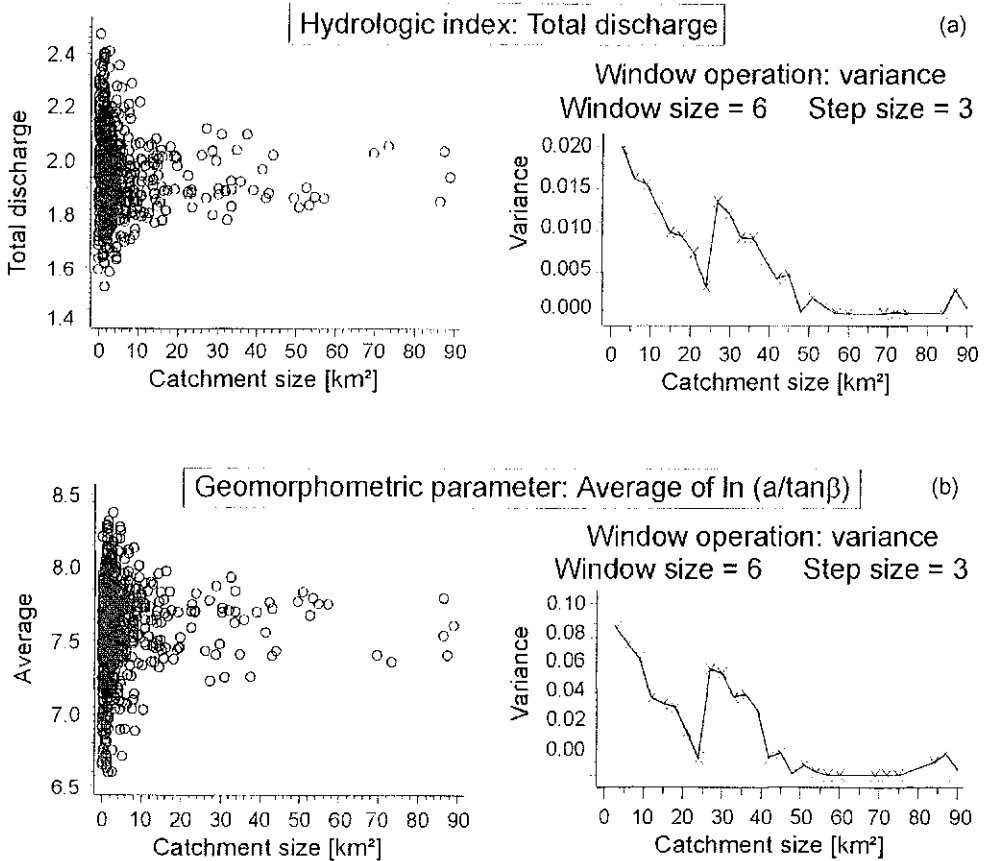


Fig. 6 Scatterplots and moving window operations over all catchment sizes at the Leinturn for (a) total discharge and (b) average of $\ln(a/\tan\beta)$. The window operation “average” reveals the average behaviour of the parameters with increasing catchment size. The window operation “variance” indicates how the variability of parameters is changing with increasing catchment size.

Table 2 Basin sizes identified according to changes in average or variance after moving window operations (Fig. 6).

| Class | Basin size x (km ²) | Number of basins |
|-------|-----------------------------------|------------------|
| 0 | <1 | 157 |
| 1 | <10 | 754 |
| 2 | $10 \leq x < 20$ | 94 |
| 3 | $20 \leq x < 40$ | 48 |
| 4 | ≥ 40 | 33 |

RESULTS

Local scale: Weiherbach

Investigations on the local scale using the SAKE model show the importance of small catchment areas in generating large contributions to runoff production. Several

geomorphometric parameters, especially flow accumulation a and the topographic wetness index $\ln(a/\tan\beta)$ correlate significantly with the catchment area and the flow depth produced by the model. Soil-geomorphometry relations seem to have high relevance for overland flow production due to the structured spatial variability of some soil parameters (Schmidt *et al.*, 1999; Merz & Bárdossy, 1998).

Statistical analysis of hydrographs produced by SAKE shows the hydrological relevance of flow length l and the new topographic parameter $\ln(a/\tan\beta)$ (Schmidt *et al.*, 1999) at small catchment scales (Fig. 4).

Regional scale: Leineturm

The clustering results of the Leineturm catchment based on SAKE and TOPMODEL (Fig. 7) hydrographs show similar spatial patterns. The TOPMODEL output has been further analysed in two ways:

- Comparing the spatial structure of the hydrological clusters and the Hammond classification (Fig. 8, mesoscale landform units derived by moving-window algorithms; Dikau, 1994; Dikau *et al.*, 1995), from which similarities can be seen for the Leineturm catchment. The hydrological clusters of Fig. 5 were reclassified based on the results of the Hammond classification (Fig. 9). Those clusters corresponding to the geomorphometric mesoforms “tablelands, hills and mountains” show high values for the variables peak discharge, total discharge and centroid lag. Small values for these variables in the area “plains and plains with hills” are represented by the remaining clusters.
- Correlations, within the class sizes obtained, with all effective geomorphometric parameters gave the following results:

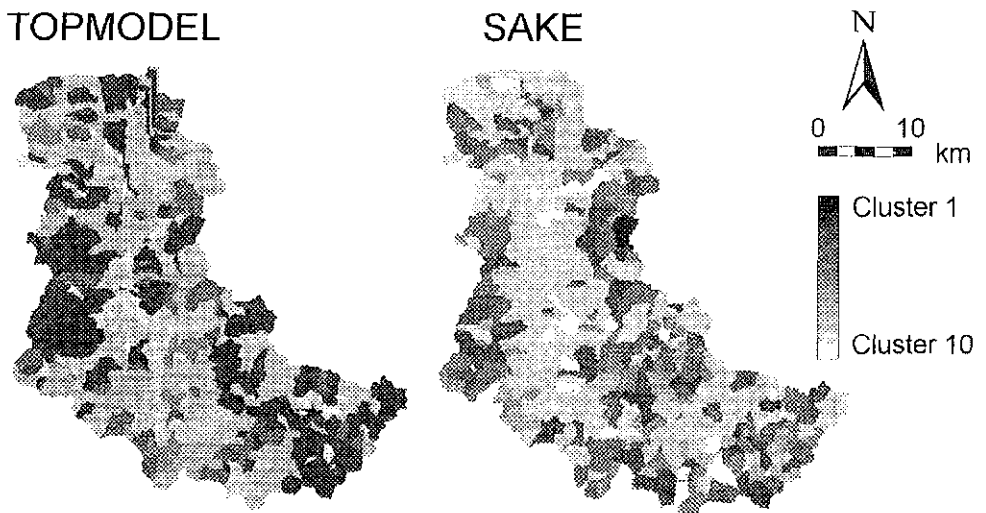


Fig. 7 Cluster analysis based on hydrograph parameters of TOPMODEL and SAKE using two factors (number of clusters: 10) and six factors (number of clusters: 15), respectively. Subcatchments have been generated using the GRASS tool *r.watershed* with a minimum threshold of 1 km² for a subcatchment (541 subcatchments).

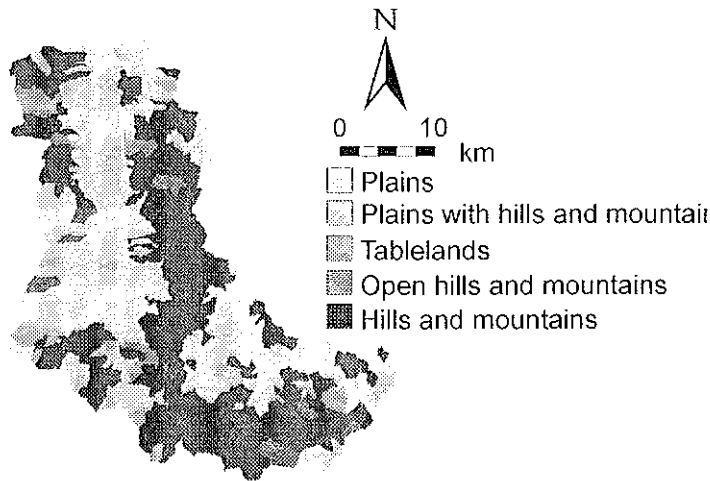


Fig. 8 Sub-basins classified according to Hammond's relief classification (Dikau *et al.*, 1995).

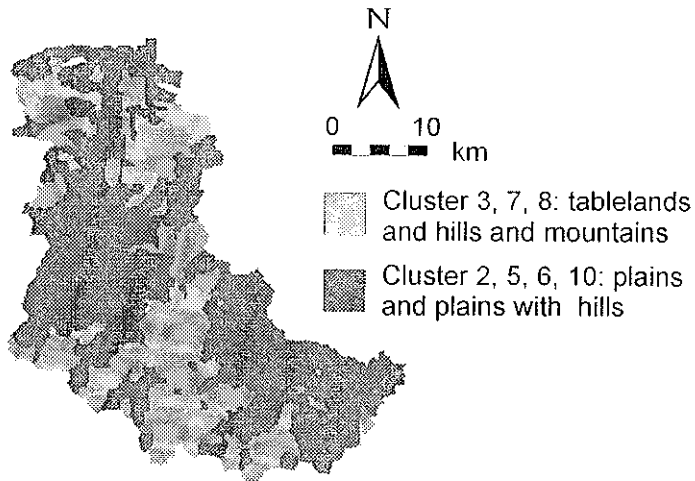


Fig. 9 Classified clusters based on the Hammond classification.

- in catchments smaller than 1 km^2 the geomorphometric index I_M (Table 1) shows the highest significance (I_M , peak discharge: $r = 0.48$) (Fig. 10). This index is an expression of relief magnitude for the drainage basins analysed;
- catchments of $0\text{--}10 \text{ km}^2$ show significant correlations for the topographic wetness index $\ln(a/\tan\beta)$ (discharge centroid, average of the topographic index: $r = 0.57$);
- in catchments of area $10\text{--}40 \text{ km}^2$ the topographic parameter $\ln(\tan\beta/l)$ correlates well with the discharge centroid (Fig. 10) (centroid, average of $\ln(\tan\beta/l)$: $r = -0.5$).
- in catchments larger than 40 km^2 only the topographic wetness index $\ln(a/\tan\beta)$ seems to be significant (discharge centroid, harmonic average of the topographic index: $r = -0.98$).

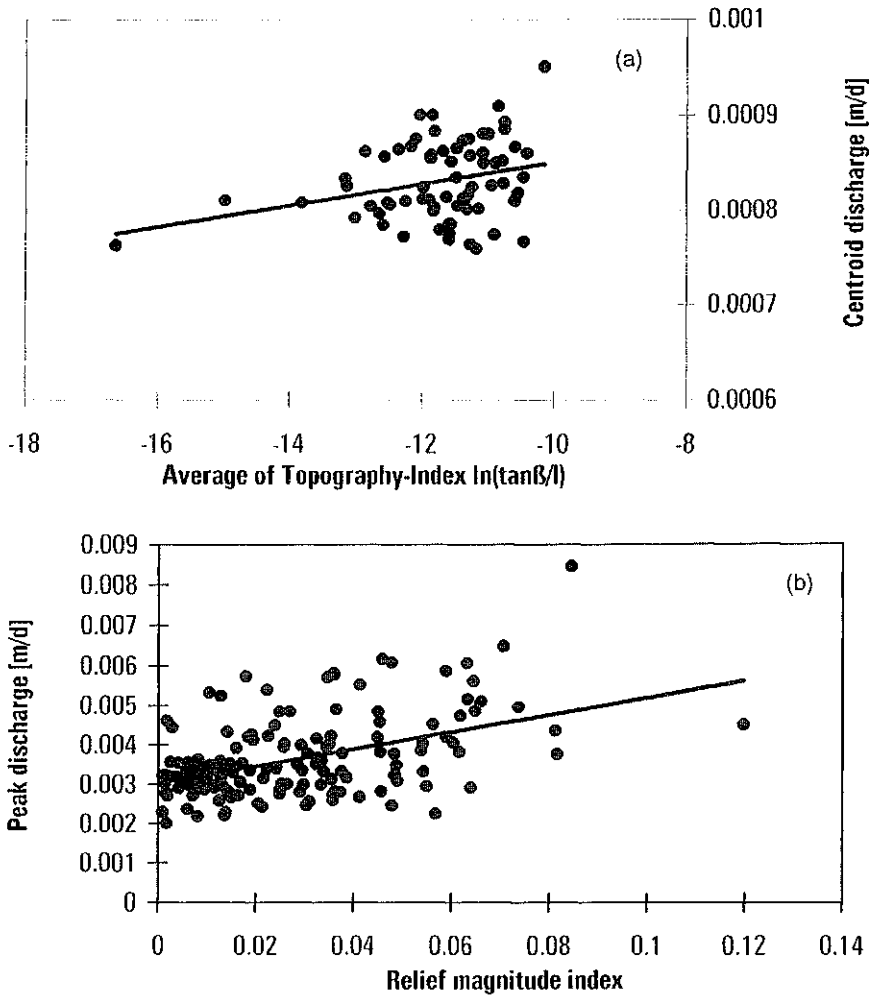


Fig. 10 Correlations of geomorphometric parameters with hydrological indices: (a) average of topography index against discharge centroid ($10 \text{ km}^2 < \text{area} < 40 \text{ km}^2$) and (b) relief magnitude index against peak discharge (catchments $< 1 \text{ km}^2$).

CONCLUSIONS

It has been shown that a detailed geomorphometric analysis enables identification of the parameters which most strongly influence the hydrograph at certain catchment scales. Correlations of geomorphometric parameters with hydrological indices depend on the scale of the investigation. For small scales, flow length and I_M correlate well with hydrological indices; in catchments ranging from 10 to 40 km^2 the topographic index $\ln(\tan\beta/l)$ shows good results; and for larger scales only the topographic index $\ln(a/\tan\beta)$ seems to be significant.

However, for large scales (catchment areas $> 100 \text{ km}^2$) geomorphometric parameters describing network topology (not part of this study) are expected to be more appropriate than parameters describing the whole catchment topography as they are related to channel routing processes.

Soil-geomorphometry relationships could be developed as a strong tool to derive the spatial variability of soil parameters from small to higher scales. Further, the general behaviour of the hydrograph (peak or total discharge) could be correlated with topographic mesoforms derived from DEMs. This research has demonstrated significant results concerning scale dependencies, but further research is needed to translate these relations into effective hydrological models.

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