

## **Regionalization of runoff formation by aggregation of hydrological response units: a regional comparison**

**G. BUSCH, J. SUTMÖLLER, J.-P. KRÜGER & G. GEROLD**

*Geographic Institute, University of Göttingen, Department of Landscape Ecology,  
Goldschmidtstrasse 5, D-37077 Göttingen, Germany*

e-mail: gbusch@mailier.gwdg.de

**Abstract** The regionalization approaches developed by the Göttingen Group were based on two contrasting regions: Eschenberg, a low-gradient agricultural area of 2 km<sup>2</sup>, and Ziegenhagen, a steep (15°) forested area of 15 km<sup>2</sup>. The variety and spatial distribution of runoff processes in the two regions were effectively derived from the generally available regional characteristics. Findings from these test regions confirmed the validity of the methods used for regionalization, and their effective scale independence.

### **INTRODUCTION**

An unsolved problem confronted by regionalization in the field of hydrology is the determination of parameters for sub-scale processes. Until now, the general practice has been to describe hydrological processes to support findings in the micro, meso and macroscale areas on the basis of the researcher's own working methods, models and solution techniques. To avoid this, there is a need to develop models which allow scale independent findings that can be transferred and applied to other geographical areas and regions (Bork, 1992; Flügel, 1995; Kovar & Nachtnebel, 1996). Within the framework of the priority programme "Regionalization in Hydrology" of the Deutsche Forschungsgemeinschaft (DFG), methods and model approaches are being developed to derive appropriate parameters from generally available regional characteristics.

The focus of the project carried out by the group in Göttingen was identification and aggregation of "hydrological response units" (HRUs) in order to reproduce the water flows of the unsaturated soil zones and the runoff formation. For this purpose, two regionalization approaches were developed which can be tested and evaluated with the help of the water balance model WASMOD, that was developed by Reiche (1991) at the Project Centre for Ecological System Research in Kiel. The employment of the model serves primarily to test the assignment of the parameters to the aggregated HRUs on the basis of simulated water flows.

### **METHODOLOGY AND REGIONALIZATION STRATEGY**

In the first regionalization approach "representative elementary areas" (REAs) were created by merging data files on plant water use, soil and geological characteristics with the geographic information system ARC/INFO (Blösch *et al.*, 1995). The water balance components evapotranspiration, surface runoff and the groundwater recharge

were then calculated for the REAs using WASMOD (Fig. 1). A cluster analysis (hierarchic agglomerative after Ward) was employed to analyse the findings and, on the basis of this, areas were compiled to create HRUs (Mucha, 1994). In the second regionalization approach, an automatic morphometric and geomorphological relief analysis was carried out on the basis of digital elevation models using the programme package SARA (Köthe, 1997). The calculated area relief units were correlated with measurements to establish the moisture content of the soil carried out over several years and the correlation between moisture content of the soil and relief units was tested with the multiple regression procedure. Four different relief units were identified statistically as HRUs; they differ significantly in the pattern of soil moisture content (Fig. 1). Soil moisture content decreases systematically from the depression areas towards convergence areas and from divergence areas *via* intermediate areas to ridge areas.

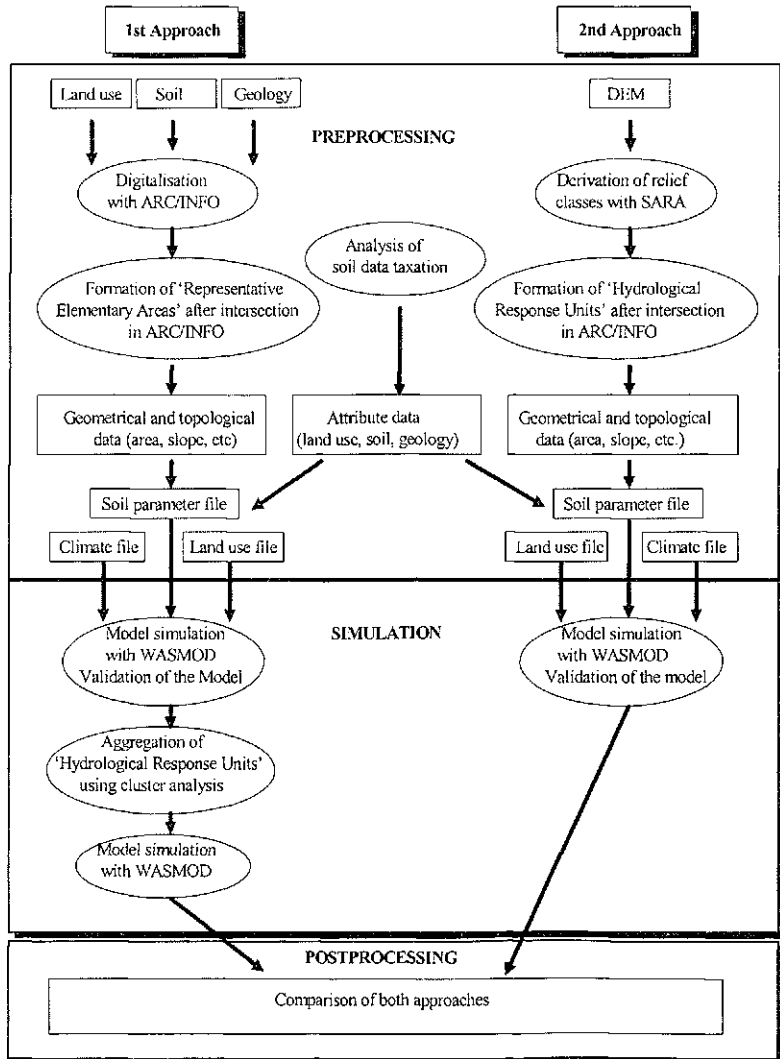


Fig. 1 Flow chart for both approaches.

For the REAs, which are defined as homogeneous, the hydrologically effective parameters can be clearly assigned. The calculation of the input parameters for the areas consolidated in the HRUs took place by weighting these areas so that dominant regional structures are emphasized (Gerold *et al.*, 1996).

These aggregation approaches were used to analyse the research regions Eschenberg and Ziegenhagen, which differ in the composition of their natural attributes. The purpose of the regional comparison is to reveal to what extent it is possible to apply the regionalization strategy independent of the region and scale.

## EMPLOYMENT OF THE REGIONALIZATION APPROACH IN THE REGIONAL COMPARISON

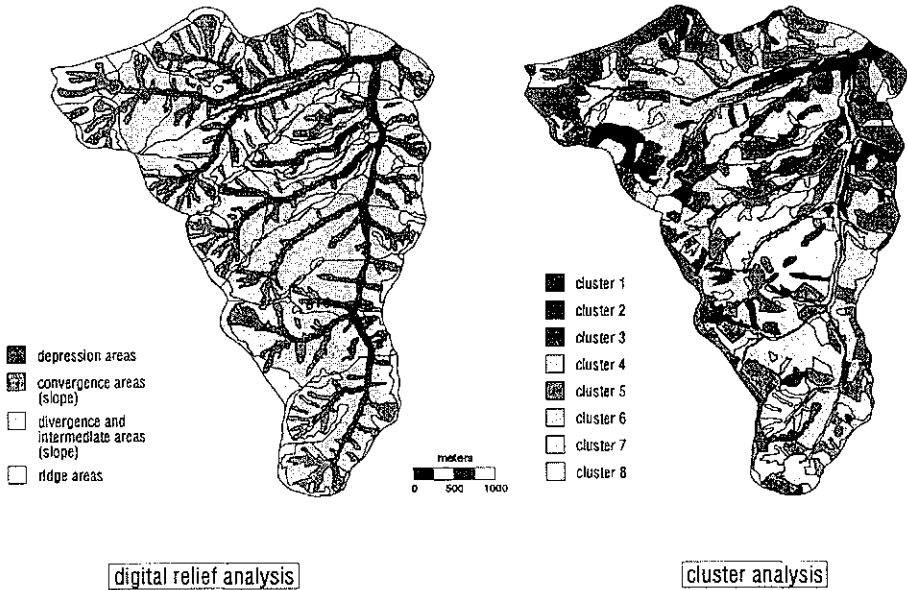
The research region Eschenberg, situated southeast of Göttingen, is just about 2 km<sup>2</sup> in extent. It is primarily used for agriculture, while the hydrology research region Ziegenhagen, which belongs to the Kaufunger forest (northern Hessen) and comprises an area of approximately 15 km<sup>2</sup>, is nearly 50% afforested. The pedological and geological characteristics of the research regions are relatively homogeneous. Braunerde to Buntsandstein (Ziegenhagen) and Pelosol to Röt (Eschenberg) represent the dominating soil types. There are clear differences with respect to slope gradient. In the Ziegenhagen region both the difference in altitude (400 m) and the mean slope gradient (approximately 15°) are twice as large as for the Eschenberg drainage basin. The Ziegenhagen region is covered to a large extent by colluvium (debris) as a result of the distinctly greater slope gradient, while in the Eschenberg region colluvium is only locally present. Due to the differences in the occurrence of colluvium, the pedo-hydrological parameters differ considerably between the two regions.

The lower slope gradient in the drainage basin Eschenberg resulted in a clearly higher percentage of midslope areas when designating the HRUs. The percentage of the area consisting of depressions and ridges is correspondingly higher in the research region Ziegenhagen. Despite the comparable resolution of the digital elevation model, the HRUs present a more differentiated picture in the case of Ziegenhagen (Fig. 2) due to the greater slope gradients.

A similar picture resulted when a cluster analysis was made. In addition to the greater number of clusters in Ziegenhagen, which can be traced to the greater variability in the composition of the area, the individual clusters cover smaller areas than in the Eschenberg region. The statistical evaluation of the cluster analysis did not reveal any significant dependence of the cluster formation with respect to geogenous and utilization-specific parameters. On the contrary, each cluster represents a factor combination of the basic input parameters statistically correlated with the water balance factors evapotranspiration, surface runoff and groundwater discharge.

The clustering of the REAs led, in both areas, to a considerable reduction in the number of units. Despite variance in the areal differentiation, the number of units comprising the aggregated geometric configurations is decreased by a factor of 2.5. Although the aggregation of the relief analysis by means of the HRUs (400 in Ziegenhagen, 163 in Eschenberg), results in a greater number of areas in comparison to the cluster analysis (268 in Ziegenhagen, 104 in Eschenberg), it is the more effective regionalization approach because the aggregation steps are carried out during the

**HYDROLOGY RESEARCH REGION ZIEGENHAGEN**



**DRAINAGE BASIN ESCHENBERG**

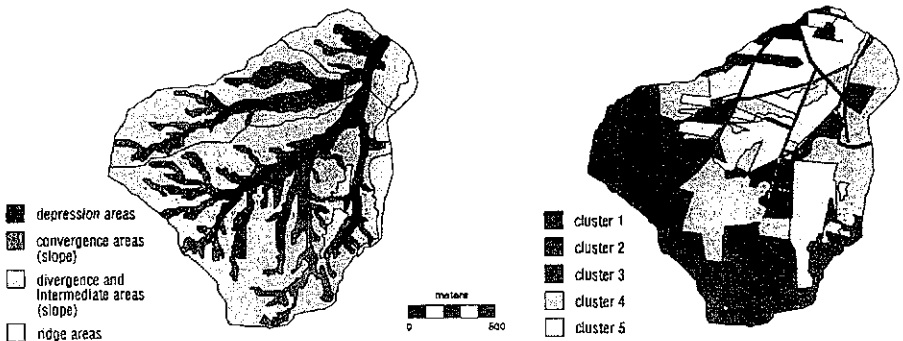


Fig. 2 Comparison of the regionalization approaches for both research areas.

pre-processing and are independent of the model, and an unambiguous and objective classification therefore ensues.

**SIMULATION RESULTS**

To simulate hydrological processes with the water balance model WASMOD, data pertaining to the weather conditions, plant water use (rooting depth, leaf area index), pedology/geology factors (texture, hydraulic conductivity, bulk density, organic carbon), and relief (slope, aspect) are necessary. Validation of the model was carried out by comparing measured and simulated hydrographs and soil moisture behaviour.

The simulation findings derived from the selected regionalization approaches do not display any significant differences. On the basis of the available geo-information covering each region, plausible results were achieved for both. There are no conspicuous differences between the two aggregation methods in the comparison of the water balances; components were correct in their size and in relation to one another.

Runoff simulations that were carried out for the period 1992–1995 register the seasonal behaviour of the runoff processes. Statistical verification of the quality of the model (Green & Stephenson, 1986) with respect to the measured and simulated hydrograph (Fig. 3) produced Pearson correlation coefficients of  $r = 0.8$  (Ziegenhagen) and  $r = 0.76$  (Eschenberg), explaining 64% and 58% of the variance respectively. The mean error for the annual simulated runoff volume was less than 30% for the period measured.

The simulated runoff behaviour for both regions was on the whole, good (Fig. 3). The dynamics of the measured runoff curve is rendered realistically, showing the increased runoff level in winter as well as the low runoff during the summer months. Individual events such as runoff peaks resulting from snowmelt are only partially correct in the current implementation of the snow module.

As there is, in all probability, significant subsurface discharge resulting from geological discontinuation in the Eschenberg region (Goldberg, 1986), the model under-estimates low flows. In the Ziegenhagen region, due to the dominant interflow components for which no allowance was made by the model, runoff peaks are exaggerated by the model, while the temporal representation is correct. Hence, the goal of simulating long-term water flows rather than individual occurrences is satisfactorily met.

Using the example of the year 1993, the water balances for the two regions are presented (Table 1) on the basis of the HRUs derived from the relief analysis. The 1993 precipitation of 924 mm (Ziegenhagen) and 661 mm (Eschenberg) did not differ appreciably from the long-term means (850 mm and 700 mm).

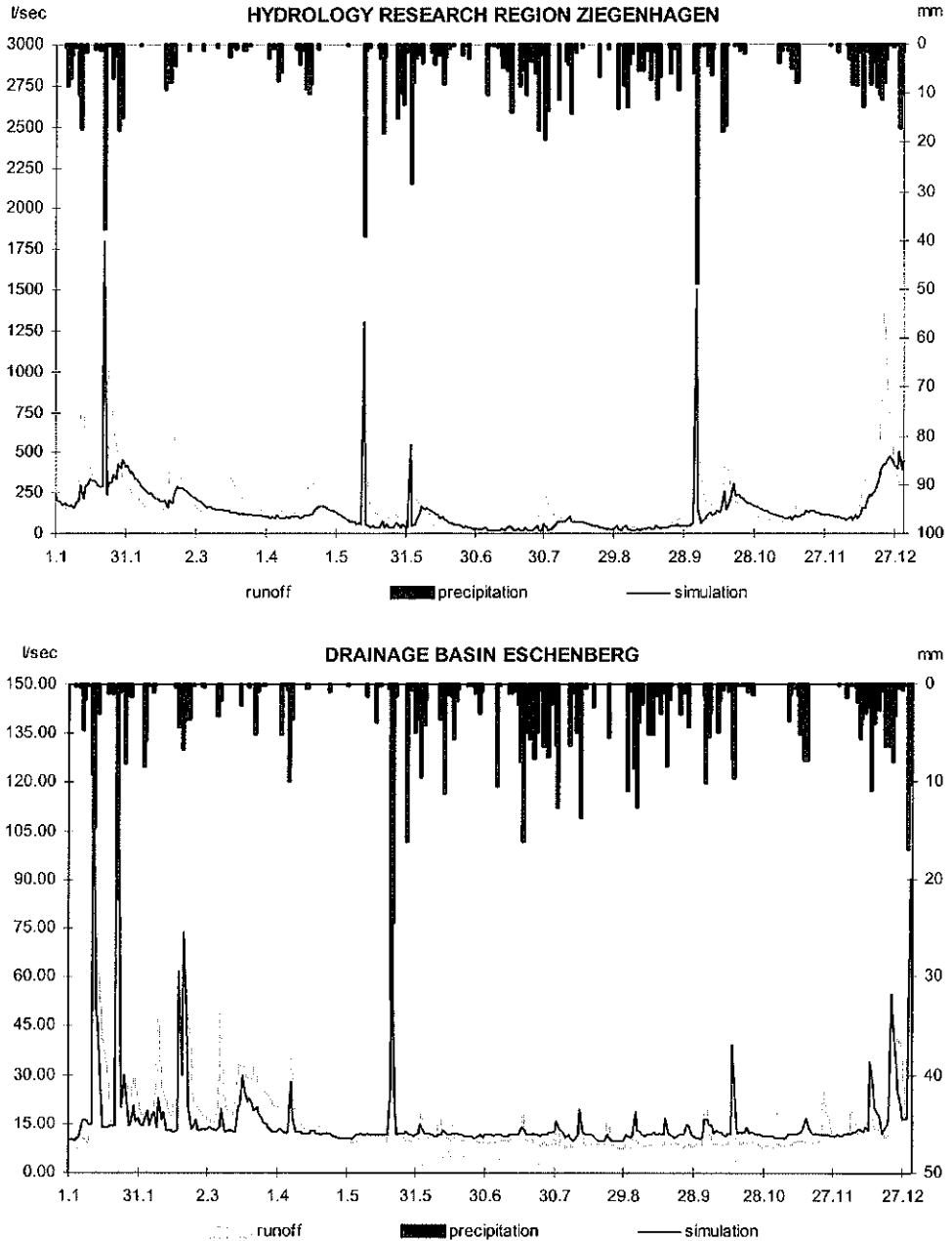
The evapotranspiration calculated for the research regions appears to be too low at less than 60% of the total balance, and inevitably causes a shift towards higher runoff.

In Ziegenhagen, which is used for forestry, evapotranspiration amounts to 59% (541 mm year<sup>-1</sup>). Interception of 24% (221 mm year<sup>-1</sup>) is higher than for the Eschenberg region (18%, 121 mm year<sup>-1</sup>), which is primarily agricultural. The influence of the vegetation and greater humus content for Ziegenhagen gives evapotranspiration of 320 mm year<sup>-1</sup> (35%), so that the groundwater discharge is clearly lower at 29% (270 mm year<sup>-1</sup>) than for Eschenberg (39%; 255 mm year<sup>-1</sup>). The greater slope gradient in the Ziegenhagen region results in twice as high a percentage of surface runoff at 6%.

**Table 1** Simulated water balances (1993); based on the HRUs from the relief analysis.

| Research area            | Precipitation | Runoff |     | Evapotranspiration |      | Reservoir |
|--------------------------|---------------|--------|-----|--------------------|------|-----------|
| Ziegenhagen              |               | GD     | SR  | ET                 | IN   |           |
| (mm year <sup>-1</sup> ) | 924           | 270    | 54  | 320                | 221  | 59        |
| (%)                      | 100           | 29.2   | 5.8 | 34.6               | 23.9 | 6.4       |
| Eschenberg               |               | GD     | SR  | ET                 | IN   |           |
| (mm year <sup>-1</sup> ) | 661           | 255    | 17  | 240                | 121  | 28        |
| (%)                      | 100           | 38.6   | 2.6 | 36.3               | 18.3 | 4.2       |

GD: groundwater discharge, SR: surface runoff, ET: evapotranspiration, IN: interception.



**Fig. 3** Measured and simulated hydrograph for 1993, based on the HRUs from the relief analysis.

These analyses substantiate the fact that it is possible to achieve plausible results with the regionalization approaches which have been developed, provided that geo-information for the entire region is available. The comparison shows that the regionalization approaches are independent of area and scale and that the differences in

the composition of the regions are reproduced correctly, both with respect to water balance and runoff behaviour. These regionalization procedures significantly improve the quality of simulation of the water balance for large drainage basins, with a significant reduction of the relational-geometric configurations produced by means of the HRUs.

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## REFERENCES

- Blöschl, G., Grayson, R. B. & Sivapalan, M. (1995) On the representative elementary area (REA) concept and its utility for distributed rainfall-runoff modelling. *Hydrol. Processes* 9, 313–330.
- Bork, H.-R. (1992) Regionalisierung bodenhydrologischer Parameter und Zustandsvariablen (Regionalization of hydrological soil parameters and watershed characteristics, in German). In: *Regionalisierung in der Hydrologie* (ed. by H.-B. Kleeberg), 201–220. Weinheim, Wellington, New York.
- Gerold, G., Suttmöller, J., Busch, G. & Krüger, J.-P. (1996) Anwendung von GIS, SARA und Wasserhaushaltsmodellierung für die Regionalisierung der Abflußbildung (Regionalization of runoff processes by application of GIS, digital relief analysis and hydrological modelling, in German). In: *Modellierung und Simulation räumlicher Systeme mit Geographischen Informationssystemen* (ed. by P. Mandl) (Proc. GISMODSIM'96), vol. 9, 41–55. Klagenfurt, Germany.
- Flügel, W.-A. (1995) Delineating hydrological response units by geographical information system analyses for regional hydrological modelling using PRMS/MMS in the drainage basin of the River Bröl, Germany. *Hydrol. Processes* 9, 423–436.
- Green, I. R. A. & Stephenson, D. (1986) Criteria for comparison of single event models. *Hydrol. Sci. J.* 31, 395–411.
- Goldberg, G. (1986) *Hydrogeologisches Gutachten zur Bemessung und Gliederung des Trinkwasserschutzgebietes für den Brunnen der Gelliehausen der Gemeinde Gleichen*. Nieders. Landesamt f. Bodenforschung, Hannover.
- Köthe, R. (1997) SARA—Ein Programmsystem zur automatischen geomorphographischen Reliefanalyse und seine Anwendung am Beispiel der Bodenkartierung. Dissertation Geogr. Inst. Univ. Göttingen (in prep.).
- Kovar, K. & Nachtnebel, H. P. (eds) (1996) *Application of Geographic Information Systems in Hydrology and Water Resources Management* (Proc. HydroGIS'96 Conf., Vienna, April 1996). IAHS Publ. no. 235.
- Mucha, H.-J. (1994) Clusteranalyse (Automatische Klassifikation). In: *Neuere statistische Verfahren und Modellbildung in der Geoökologie* (ed. by W. Schröder *et al.*), 109–127. Vieweg, Braunschweig/Wiesbaden.
- Reiche, E. W. (1991) Entwicklung, Validierung und Anwendung eines Modellsystems zur Beschreibung und flächenhaften Bilanzierung der Wasser- und Stickstoffdynamik in Böden. *Kieler Geogr. Schr. Report no. 29*.