Soil–Vegetation–Atmosphere Transfer Schemes and Large-Scale Hydrological Models (Proceedings of a symposium held during the Sixth IAHS Scientific Assembly at Maastricht, The Netherlands, July 2001). IAHS Publ. no. 270, 2001.

Large-scale modelling and spatial heterogeneity of landscape characteristics—experience from the Upper Danube River basin

JOACHIM GEYER & ANDREAS H. SCHUMANN

Institute for Hydrology, Water Management and Environmental Engineering, Ruhr-University Bochum, Universitätsstraße 150, D-44780 Bochum, Germany

e-mail: andreas.schumann@ruhr-uni-bochum.de

Abstract This study presents the application of a SVAT model for the design of a macroscale hydrological model. For a climate change study, a large number of scenarios is used to assess the risk of changes in runoff conditions for the Upper Danube basin (~4000 km^2). The paper emphasizes the adequate derivation of the spatial structure of the catchment, which has to fulfil two requirements. On the one hand, the spatial variability of the catchment characteristics has to be obtained to allow a physically-based representation of the relevant hydrological processes. On the other hand, the number of spatial units that can be considered is very limited, owing to the computational effort caused by the huge number of scenarios. Consequently, the most important catchment characteristics, which govern the spatial variation of the relevant hydrological processes, have to be identified. The derivation of a ranking of characteristics regarding their influence on different processes is presented in the case study.

Key words macroscale modelling; spatial units; catchment characteristics; sensitivity analysis; Danube basin

INTRODUCTION

The heterogeneity of landscape characteristics and, resulting from it, of the hydrological processes, leads to distributed hydrological models in cases where the catchment is divided into small, regularly or irregularly shaped area elements based on these characteristics. The question arises as to how these area elements can be defined. Some options are:

- to subdivide the catchment into so-called "hydrological response units" (HRUs), which are similar with regard to selected characteristics and which are modelled separately, as in, e.g. the Precipitation-Runoff Modelling System (PRMS) of Leavesley & Stannard (1995);
- to subdivide the catchment into equally-spaced square grid elements and to represent the hydrological processes in these units by a parameter set in which the physical characteristics of the units are considered. An example is the model for the Rhine River, which is based on a subdivision of the river basin into 3-km^2 grid elements (Kwadijk & Rotmans, 1995).

If we intend to divide a river basin into hydrologically similar parts, each of which is similar in its physical characteristics (e.g. land-use categories, soil texture classes, topography), the problem arises as to which characteristics should be considered as relevant to the hydrological processes. If too many different characteristics are considered (e.g. all topographical characteristics relevant to hillslope processes), the partitioning will be very detailed. If we consider only some characteristics in this subdivision, we neglect the heterogeneity of the others. In addition, in a process-based subdivision of a catchment, the problem of heterogeneous distributions of meteorological variables (e.g. precipitation and temperature) has to be taken into account (Schumann & Geyer, 2000).

This latter problem does not exist if we divide the catchment into grid-based units. For each grid cell, the specific value of its precipitation or temperature can be estimated. However, the physical characteristics within each grid cell may be heterogeneous. If we were to reduce the size of the grid cells, this heterogeneity would be reduced, but the disadvantages of a very detailed resolution are that there would be an increase of the computational requirements, and that the model structure would become more complex due to the need to describe more interactions among the small spatial units.

In this study, both approaches are utilized in a two-step procedure to combine the advantages of both disaggregation methods. First the catchment is discretized by the grid approach with a very high resolution, thus using the whole available spatial information, minimizing the heterogeneity within the cells and taking the spatial distribution of the meteorological input into account. In the second step, the analysis of the spatially-distributed results of relevant variables allows the identification of homogenous and heterogeneous regions and the determination of the important catchment characteristics which cause these variations and consequently the derivation of hydrologically similar units based on these characteristics. The application of the hydrological unit approach enables both the representation of the spatial variability of the processes and the reduction of computing time to an acceptable amount.

PROCESS-ORIENTED SPATIAL DISTRIBUTION FOR THE CASE STUDY

For a climate change study for the Upper Danube basin in the southern part of Germany, a large number (25 000) of climate change scenarios was used to make an assessment about the risks of changes in the runoff conditions. As these scenarios were provided for the very coarse spatial resolution of a general circulation model (GCM), a large river basin was chosen to transfer these scenarios into hydrological information to reduce the scale effect. With regard to the specific hydrological conditions in this region, the largest available catchment—the Upper Danube basin—has an area of 4000 km^2. In comparison to the spatial scale of GCMs, this river basin is relatively small. However, the spatial heterogeneity of different landscape characteristics and the challenges of the huge amount of scenarios, which have to be transmitted by the model into hydrological information, demand new ways of modelling and parameterization.

The physically-based model chosen for this study has to be applied and validated for the period representing the actual climatic situation, in this study covering 46 years from 1951 to 1996. A sketch of the simplified vertical structure of the model is given in Fig. 1.

The first step to derive an appropriate spatial structure of the model consists of a subdivision of the river basin into three hydrological fundamentally different responding

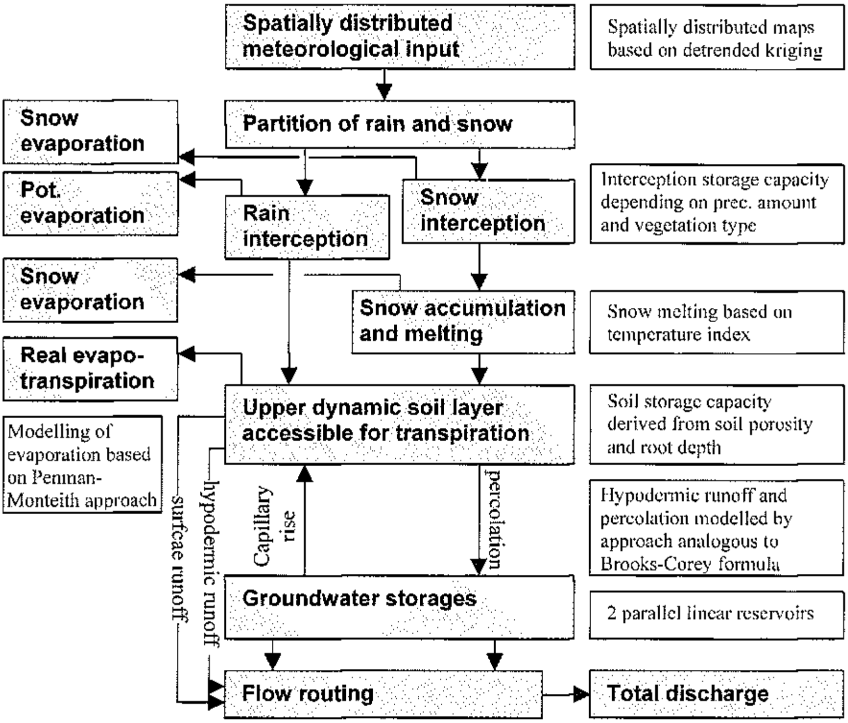

Fig. 1 Simplified vertical structure of the hydrological and SVAT model.

regions (see also Fig. 2(a)): (a) the gravel plains at the foothills of the Alps, providing the major part of the Danube water (35% of catchment area); (b) the Swabian Mountains dominated by extensive karst areas (45%); and (c) the Black Forest Mountains, a mid-elevation mountainous area (20%). For each of these regions, a specific model parameterization was applied.

The regions themselves were classified into "homogeneous" units based on distinct GIS analysis of their relevant characteristics. The process-oriented spatial discretization of the catchment area into hydrological units should be chosen by considering the spatial variability of the most relevant hydrological processes. The number of these units is restricted due to the high number of scenarios that have to be modelled and the limited computer resources. The challenge consists in the identification of the most effective characteristics that govern the spatial variation of the hydrological processes.

The two-step procedure indicated in the introduction is chosen to rank the relevance of the different catchment characteristics. At first the model is run for a short but representative time period of one year (April 1993–March 1994) with the highest applicable spatial resolution. Here a cell size of 250 m × 250 m was utilized, which results in about 65 000 elements for the Upper Danube catchment.

The investigation of the spatially-distributed results of this model run, which targets the derivation of the most relevant characteristics, is presented in the following for the hydrological processes considered to be important in this study: runoff generation, potential and actual evapotranspiration.

Spatial distribution with regard to runoff generation

Figure 2 shows the spatially-distributed results of the high resolution model run. Presented are: a map of the mean daily precipitation values of the one-year period

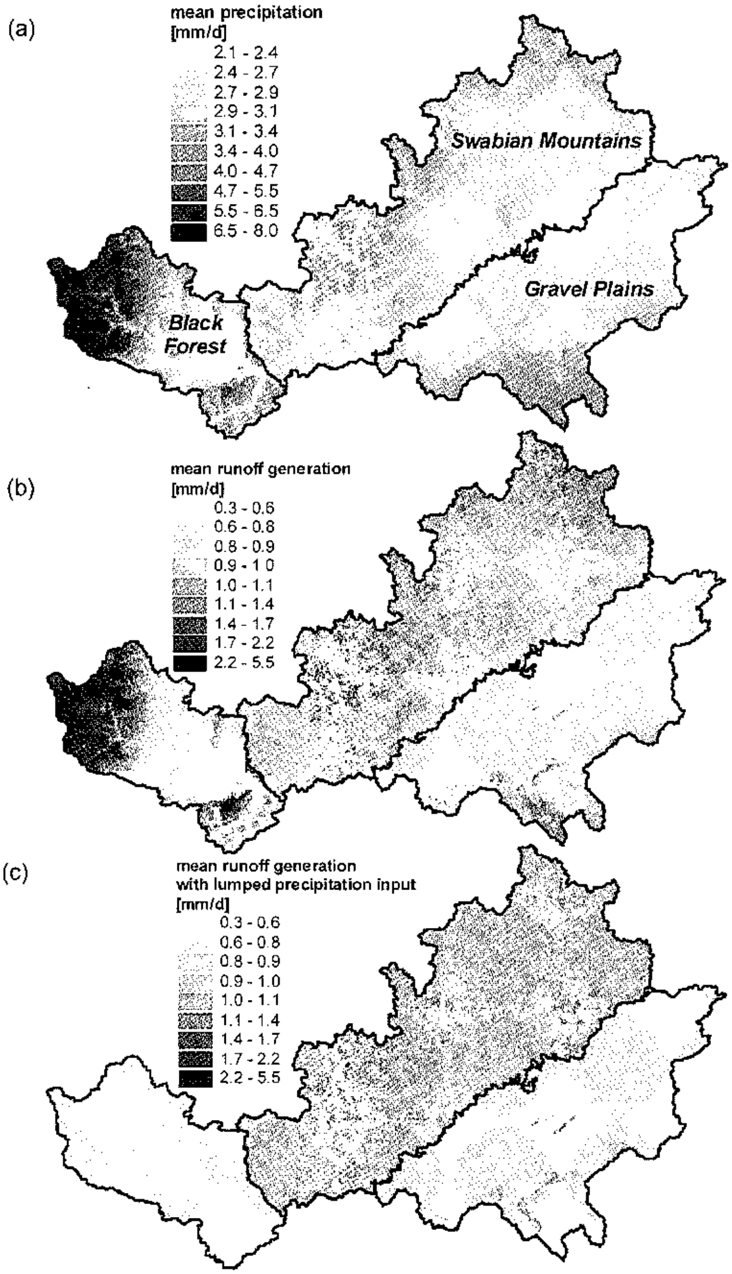

Fig. 2 Spatial distribution of (a) mean daily precipitation, (b) runoff generation and (c) runoff generation by application of lumped precipitation input.

input derived from geostatistical distributed precipitation maps (Fig. 2(a)), the mean annual runoff generation using the spatially-distributed precipitation input (Fig. 2(b)), and the mean annual runoff generation under the assumption of a lumped precipitation input (Fig. 2(c)). As runoff is highly correlated with the precipitation, significant variations of runoff generation are mainly determined by the spatial variability of precipitation. If only a lumped precipitation input is available, the simulations show a considerable lack of variation, as shown in Table 1. There the coefficients of variation of runoff generation and distributed precipitation are listed for the three different natural units of the river basin. The spatial variabilities of the precipitation differ in the three regions as a result of orographic effects. High variability in precipitation also causes high variation in runoff generation, as can be seen in the Black Forest Mountains. In other parts of the river basin (in the Swabian Mountains), the relatively low variability of precipitation is reflected also in a rather low variability of runoff. The reduction of runoff variability which follows the use of lumped precipitation is considerable. Obviously, the adequate spatial representation of the precipitation input is very important for a proper identification of the spatial distribution of runoff generation in mountainous regions. As the mean daily precipitation values are strongly correlated with elevation in the mountainous parts of the river basin, a precipitation–elevation relationship seems to be adequate to improve computations of long-term water balances. That is why elevation is chosen here as the most relevant characteristic with regard to runoff generation. The remaining variation of the runoff distribution is determined by the soil storage behaviour and actual evapotranspiration.

Table 1 Variation coefficients of precipitation and runoff generation for the three main regions of the Upper Danube catchment.

	Spatially distributed precipitation	Runoff generation based on spatially dist. precipitation input	Runoff generation based on lumped precipitation input
Black Forest Mountains	0.376	0.494	0.128
Gravel Plains	0.132	0.146	0.055
Swabian Mountains	0.081	0.092	0.060

Spatial distribution with regard to evapotranspiration

Potential evapotranspiration (*ETp*) is mainly driven by energy supply and vapour transport. The evapotranspiration model is based on the Penman-Monteith approach parameterized by an adapted MORECS scheme (Thompson *et al.*, 1981). Account has to be taken of the fact that evaporation out of the interception storages is not being included in the potential evaporation values presented in this study. As this model evaporates preferentially the content of interception storages, the *ETp* of forests is lower than that of pasture or cropland, as forest has a higher storage capacity for interception. Considering that the wind field can not be described due to a lack of data, temperature remains the main source of variability among the meteorological forcing variables. The influence of aspect and slope of the land surface can be neglected. In an analysis of the effects of relief on *ETp*, considerable variation appears only in the mountainous region of the Black Forest. With regard to the long-term balance, the

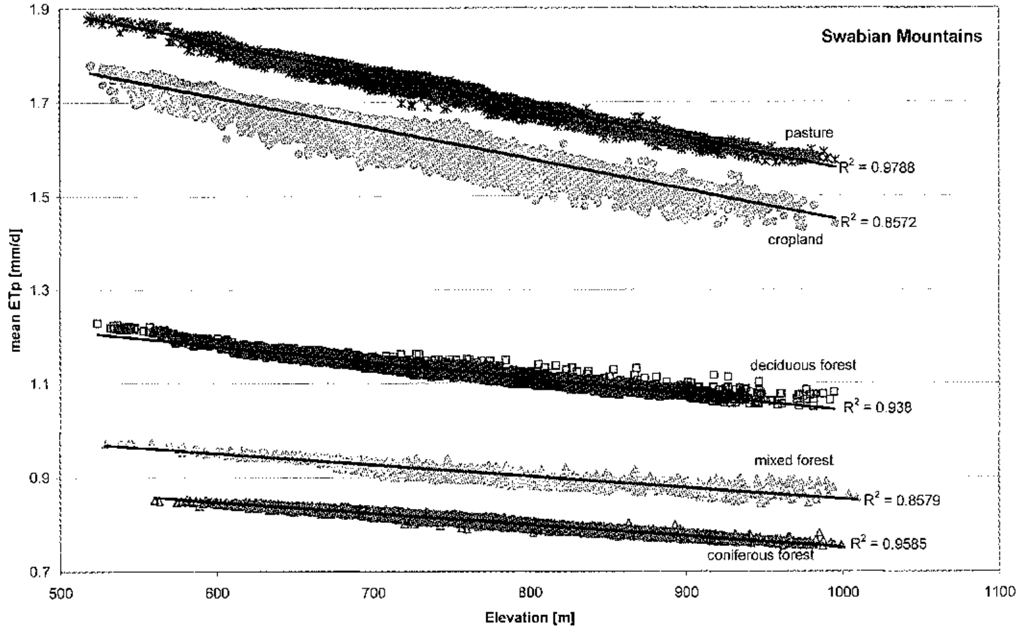

Fig. 3 Scatterplot of elevation *vs* mean daily potential evapotranspiration for the Swabian Mountains region.

differences of mean values of *ETp*, with and without consideration of topography, are only 4%. Since the spatial variation of temperature depends on elevation, this characteristic is also very important for the potential evapotranspiration. To demonstrate this, the example of the Upper Danube River basin in Fig. 3 shows the scatterplot of *ETp vs* elevation for all grid cells of the Swabian Mountains region. To estimate the importance of elevation, we have to differentiate between types of vegetation. Then we can derive significant relationships between elevation and *ETp* which describe 76–99% of the variances of the potential evapotranspiration within this river basin. The different slopes of the derived regressions for each type of vegetation are caused by the different parameterizations of stomata and aerodynamic resistances, vegetation densities, etc.

The actual evapotranspiration (*ETa*) depends on the same factors as *ETp*, but in addition we have to consider the control of the process of evapotranspiration by water supply from the upper soil layer which becomes accessible for transpiration. The reduction of *ETp* to *ETa* is modelled by an approach by Minhas modified by Disse (1995). The importance of the soil water becomes evident if we analyse the relationship between the elevation and the actual evapotranspiration *ETa* (Fig. 4). Here, the correlation to elevation is relatively weak, especially for forested areas where only 30% of the variance of *ETa* is explained by elevation. This difference in the behaviour of potential and actual evapotranspiration is caused by the water availability of the soil. In Fig. 5(a), the importance of the mean relative soil storage content of the upper soil layer for *ETa* is shown in the example of the gravel plain area. At first sight this relationship seems to be rather diffuse, but a relationship between the relative soil storage content and the actual evapotranspiration becomes evident if we look at one specific type of vegetation only. As an example, Fig. 5(b) shows the scatterplot for

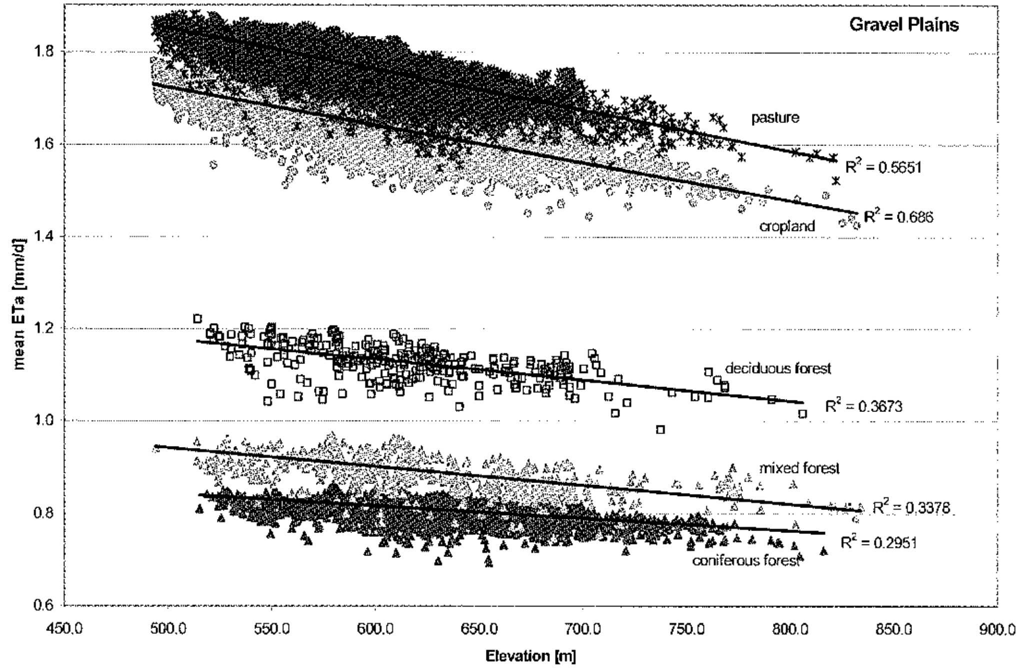

Fig. 4 Scatterplot of elevation *vs* mean daily actual evapotranspiration for the Gravel Plains region.

only coniferous forests, with a further differentiation of the data by the soil types. After distinguishing different vegetation and soil types a relatively strong relationship between the relative soil storage content and *ETa* becomes obvious. The soil type governs the relative soil storage content. This is caused by another characteristic which is derived from the soil type, the saturated hydraulic conductivity. This conductivity is decreasing from a low storage content determined by texture of sand to the higher average value of the relative storage content of texture of clay (in Fig. 5(b) from the left to the right). The still remaining spatial variability of the actual evapotranspiration can be explained by the soil porosity (field capacity) and the capillary rise. This variability could be described by a topographic index.

The type of vegetation is the main factor which determines potential and actual evapotranspiration. Elevation is less important in explaining the spatial variability of the actual evapotranspiration, especially for forested areas. More important (at least in our case study) is the influence of the soil storage content, which depends on the hydraulic conductivity, or, more generally, on the soil texture.

HYDROLOGICAL UNITS IN THE UPPER DANUBE BASIN

The analyses described above, using a differentiation of hydrological units by elevation class and vegetation type as the principal factors determining the spatial variability of runoff generation and evaporation, were undertaken for the Upper Danube basin. The resulting number of about 50 hydrological units is a compromise between a

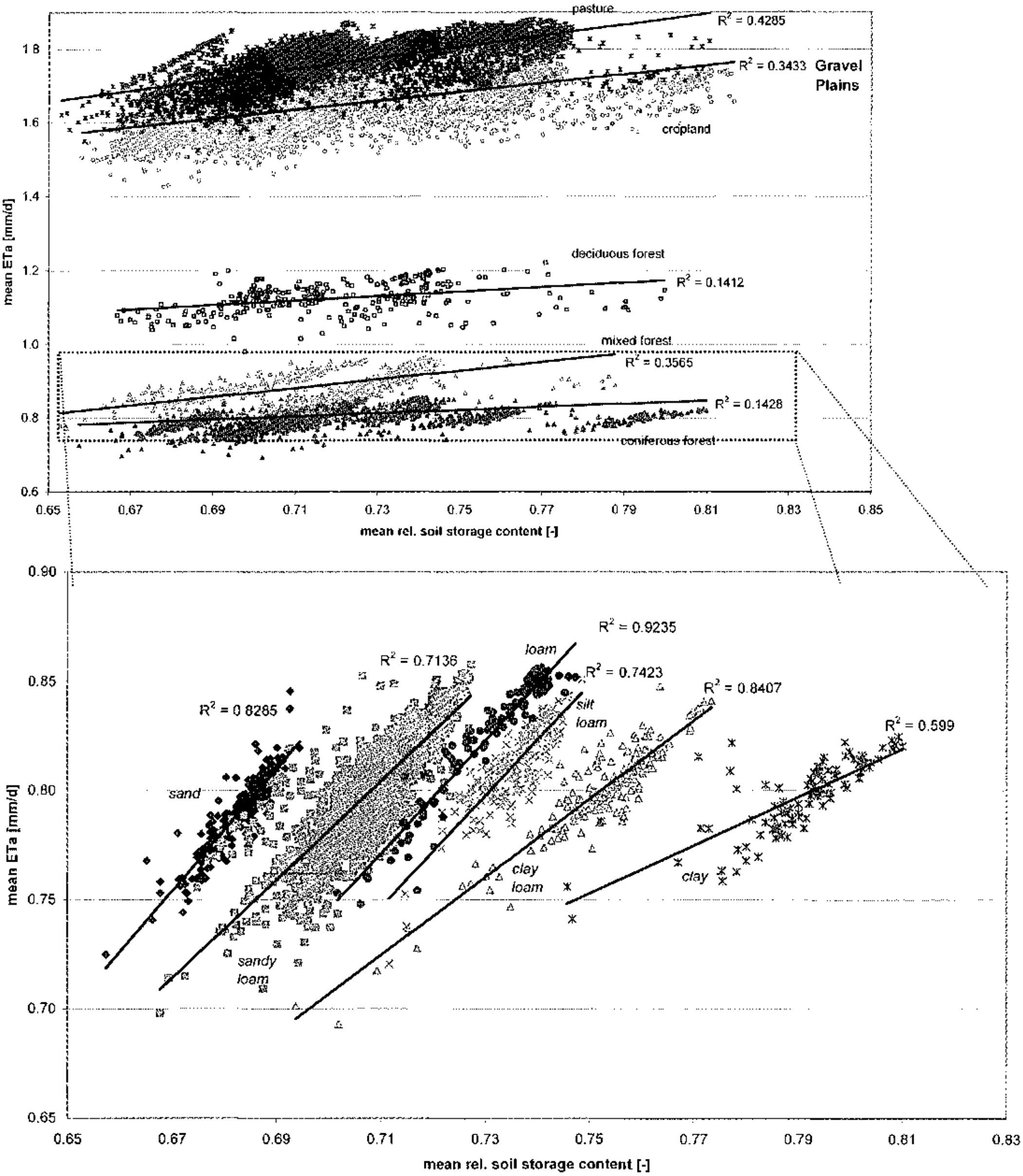

Fig. 5 (a) Scatterplot of mean relative soil storage content *vs* mean daily actual evapotranspiration for the Gravel Plains region differentiated by vegetation type, and (b) scatterplot of coniferous forest differentiated by soil type.

minimal number of units and the need to represent the variability of hydrological processes. Despite the spatial units being relatively large, the water balance of the time period 1951–1996 was accurately described. The performance of the model is shown in Table 2. The model is also able to describe wet and dry periods with the same accuracy.

Table 2 Statistical measures of the discrepancy between simulated and observed discharges for the Upper Danube basin (1951–1996).

Month / season	Observed mean runoff (mm)	Simulated mean runoff (mm)	Mean absolute error (mm)
January	30.9	33.1	5.2
February	33.2	31.1	9.1
March	38.1	38.0	6.7
April	35.5	34.5	5.7
May	27.0	24.3	4.7
June	23.7	22.3	5.1
July	19.6	19.5	5.5
August	16.7	16.9	4.0
September	13.6	13.8	3.1
October	15.1	15.9	3.2
November	19.2	21.2	4.6
December	28.7	29.9	5.7
Summer May-Oct.	115.5	112.8	13.5
Winter Nov.-Apr.	185.6	187.6	13.6
Year	301.2	300.6	20.5

CONCLUSIONS

The spatial distribution of a hydrological model can be chosen by considering the heterogeneity of hydrological processes. To describe this heterogeneity we can use SVAT models for a limited time period (e.g. one year) at a high resolution. By analysing the results we can assess the importance of spatially-distributed characteristics for different hydrological processes (e.g. runoff generation or actual evapotranspiration). Based on this assessment, we can structure a macroscale model which uses the same process descriptions as the SVAT model, but with a coarser resolution. By complex analysis with a SVAT model it is possible to define a distributed model which takes account of the variability of the catchment characteristics and their specific importance for hydrological processes. With the derived model, we were able to compute the changes in the water balance of the upper Danube for a large number of climate scenarios (25 000 scenarios, derived from Monte-Carlo simulations).

REFERENCES

Disse, M. (1995) Modellierung der Verdunstung und der Grundwasserneubildung in ebenen Einzugsgebieten (Modelling evaporation and groundwater recharge in flat watersheds, in German). PhD Thesis, *Mitteilungen des Instituts für Hydrologie und Wasserwirtschaft der Universität Karlsruhe*, 53.

Kwadijk, J. & Rotmans, J. (1995) The impact of climate change on the River Rhine: a scenario study. *Climatic Change* **30**, 397–425.

Leavesley, G. H. & Stannard, I. G. (1995) The precipitation–runoff modelling system PRMS. In: *Computer Models of Watershed Hydrology* (ed. by V. P. Singh). Water Resources Publications, Littleton, Colorado, USA.

Schumann, A. H. & Geyer, J. (2000) GIS-based model for considering spatial heterogeneity of catchment characteristics. *Phys. Chem. Earth* B **25**, 691–694.

Thompson, N., Barrie, I. A. & Ayles, M. (1981) The Meteorological Office rainfall and evaporation calculation system: MORECS. *Hydrol. Memo. no. 45, Met Office, Bracknell, UK.*