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Application of GIS for hydrological modelling in high mountain areas of the Austrian Alps

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Abstract A geographical information system (GIS) was applied to the hydrological modelling in the Glatzbach River basin which is located very close to Großglockner in the Hohe Tauern mountain range of the Austrian Alps. A hydrological model based on TOPMODEL (Beven *et al.*, 1995) was adopted and used to model the hydrological response of the basin. To generalize TOPMODEL further provision was made to include a snowmelt routine, the calculation of potential evapotranspiration, hydrological routing and an infiltration algorithm into the model. As an additional part of this study the model components have been evaluated against field measurements wherever data were available. Then the generalized model was calibrated against a 50-day time series of measured runoff for the year 1989. This model calibration was evaluated for the years 1990 and 1996. A comparison between observed and simulated runoff on an hourly basis illustrates that they match well in distribution and volume for this high mountain basin using the generalized TOPMODEL version.

INTRODUCTION

The high mountain areas of the earth play a central role in the global hydrological cycle since there has been relatively little research carried out in these areas. At the site of the headwaters especially, there is a very incomplete picture of how these sites control the runoff and floods in the lower valleys of the Alps. These gaps in our knowledge are a result of a combination of factors (weather, height and distance) due to the extreme location. Despite this relatively much effort has been made within the Austrian Man and Biosphere (MaB) Programme to study the water balance, runoff and infiltration conditions of different soil–vegetation complexes in the Alpine region of the Großglockner.

For many years research has been done with respect to geomorphological and hydrological processes within the Glatzbach River basin. The University of Bamberg established two instrumented subcatchments—corresponding to the differentiation of the basin with its vegetation cover—and a main gauging station within the basin (Höfner, 1993). In 1995 the Institute of Torrent and Avalanche Control (WLS) took over the three existing V-notch weirs from the above-mentioned university and equipped the weirs with digital discharge-measurements. The WLS also set up a meteorological station, which allows digital recording of the most important hydrological variables with a high time-resolution. The data provided will be used to test different hydrological models for their reliability in the catchments of Alpine torrents.

STUDY AREA

The study area is located in the eastern Tyrol very close to Großglockner in the Hohe Tauern Mountain range of the Austrian Alps. The small basin (1.4 km^2) ranges from 2440 to 2920 m above sea level. The Glatzbach River himself is a tributary of the River Leiterbach, which drains near Heiligenblut into the River Möll. Within the basin the average annual temperature is less than -2°C, cumulative precipitation is from 1300 to 1750 mm $year^{-1}$ including storage in the quality of snow with an amount to 600 mm.

The rock base consists mainly of phyllites and calcareous mica schists and is covered by about 50% with morainic and gelifluctional material. Due to the postglacial repetitive alternation of morphodynamic activity and stability within the periglacial belt initial soils and well developed soils such as Alpine brown earths and Alpine pseudogleys occur. With regard to the vegetation the catchment can be divided into an Alpine tundra belt (2450–2650 m a.s.l., vegetation cover over 95%) and a predominantly vegetation-free subnival frost-shattering zone (2650–2900 m a.s.l., vegetation cover 14%) (Böhmer, 1993).

DATA

Primary data of elevation include a 10 m square grid, derived by the Institute of Surveying, Remote Sensing and Land Information BOKU (Vienna), as well as flow paths and sinks, which have been digitized on the basis of land surveys and an orthophoto of the basin. To set up a hydrologically sound DTM, surface fitting was carried out by means of TOPOGRID (Hutchinson, 1988). The algorithm of Hutchinson was preferred since as it allows the interpolation of the surface from several topographic data and the elimination of apparent sinks by drainage enforcement in a single calculation step. A three-dimensional view of the basin was obtained by draping an orthophoto over the DTM and is shown in Fig. 1.

In the area being studied no soil samples were taken. Therefore the soil types were deduced from the vegetation communities which have been transferred to the GIS on the basis of an infrared orthophoto. The soil parameters for the different soil types were taken from sprinkler experiments and soil surveys from the MaB Programme. Within the scope of the MaB Programme Neuwinger (1989) showed that it is possible to define the limit of these Alpine soils from vegetation and infrared orthophotos.

The rainfall and runoff data series for the years 1989 and 1990 were quoted from Höfner (1993) and for the year 1996 measurements for these were taken by the WLS (Scherz, 1998). Temperature, wind and relative humidity were interpolated from the Kals station (1347 m a.s.l.) for 1989 and 1990 and were measured locally for 1996.

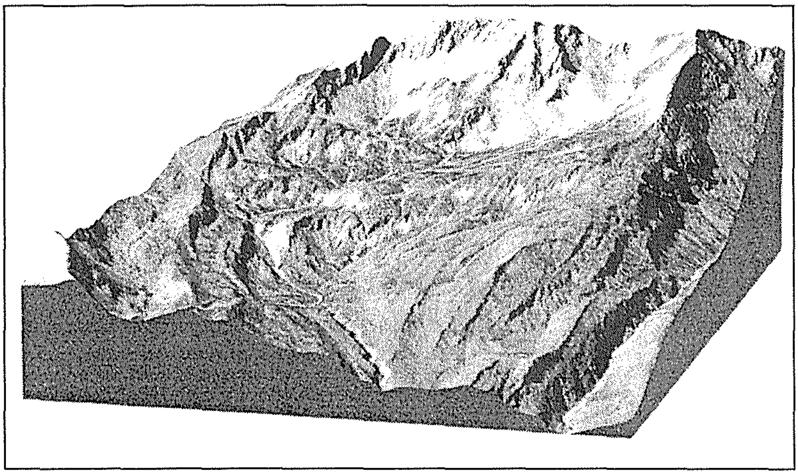

Fig. 1 *Digital 3D-view of the study area from the southeast.*

Snow depletion curves were derived from field surveys in the snowmelt season of 1995 (Ellmer, 1997).

METHOD

The decision to use the TOPMODEL concept was because: (a) topography can be incorporated easily in the form of a DTM within the model as it plays an important role in the hydrology of Alpine regions; (b) there are few parameters to be calibrated, (c) it is well documented, and (d) it is mathematically straightforward. However, certain modifications had to be made to adopt TOPMODEL to Alpine circumstances, which will be outlined below. For the present study a GIS has been set up for data preparation and analyses, which also includes topography, vegetation, the river network and digital orthophotos.

For modelling purposes, rainfall was assumed constant for the whole basin even though subcatchments have unique vegetation and soil parameters. The Topoindex was calculated from the DTM with the multiple flow algorithm of Quinn *et al.* (1995). An overlay of the Topoindex (Fig. 2) on the vegetation communities (subcatchments) was done to obtain the distribution of the Topoindex for each. The Topographical Index has been differentiated into 30 classes representing different saturation capacities with the appropriate calculation of soil moisture for each class. A comparison between the Topographical Index and the Ecological Wetness Index (Ellenberg, 1986) by means of several vegetation communities within the basin led to a correlation factor of nearly 0.6 (Fig. 3) and demonstrates the applicability of the Topoindex in this Alpine area.

The infiltration algorithm of Green and Ampt based on a method of Chow *et al.* (1988) was included within the model which allows the calculation of surface runoff by variable rainfall intensities. The parameters for this routine were derived from sprinkler experiments on different soils within the MaB Programme (Blümel & Klaghofer, 1980).

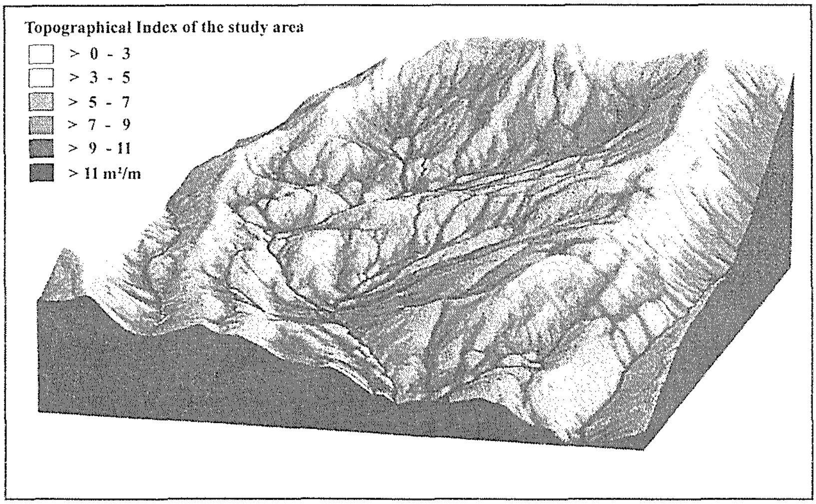

Fig. 2 Topographical Index of the Glatzbach River basin.

The transformation of potential evaporation (PET) to actual evapotranspiration (AET) was done by a crop coefficient, which was derived from the difference between the calculation of PET with the Combined (Aerodynamic and Energy Balance) Method (Chow *et al.*, 1988) and lysimetric measurements taken from the MaB (Körner, 1978) (Fig. 4). In order to scale up AET spatially distributed radiation was calculated by the DTM over five seasonally varied days within the year 1995 thus obtaining the most accurate AET possible. Due to the lack of data in the years 1989 and 1990 an aerodynamic approach was included in TOPMODEL in spite of the fact that the Combined Method provided the best results. The recalculation of the

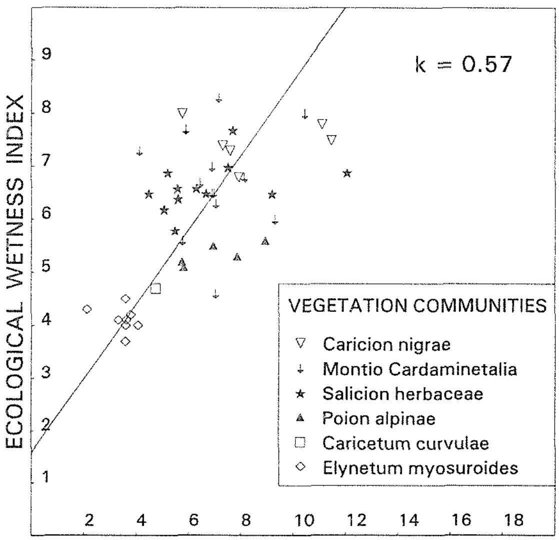

Fig. 3 Comparison between the Topographical Index and the Ecological Vegetation Index of Ellenberg for different vegetation communities.

crop coefficient for the aerodynamic approach was done by comparing the results with those of the Combined Method.

A snowmelt algorithm, based on the Degree-day-factor Method was incorporated into the hydrological model. Snow depletion curves for each subcatchment have been computed from field investigations of Ellmer (1997), who mapped the snow-covered areas in an interval of about 10 days in the spring of 1995. Assuming that snow depletion patterns are similar from year to year a relation between the sum of positive temperature and the proportion of the snow-covered area could be obtained from the mapped snow patterns. Ellenberg (1986) described the good correspondence between vegetation communities and snow depletion patterns which could be also detected in the present study. The Degree-day Factor was assigned uniformly to the whole basin and has been calibrated on the basis of the hydrograph of 1989. However, it was necessary to assign the TOPMODEL parameters separately for each subcatchment. This has been done by comparing the properties of the different soil types taken from soil investigations of the MaB Programme and by an interpretation of the hydrographs of the two instrumented subcatchments. Afterwards the model

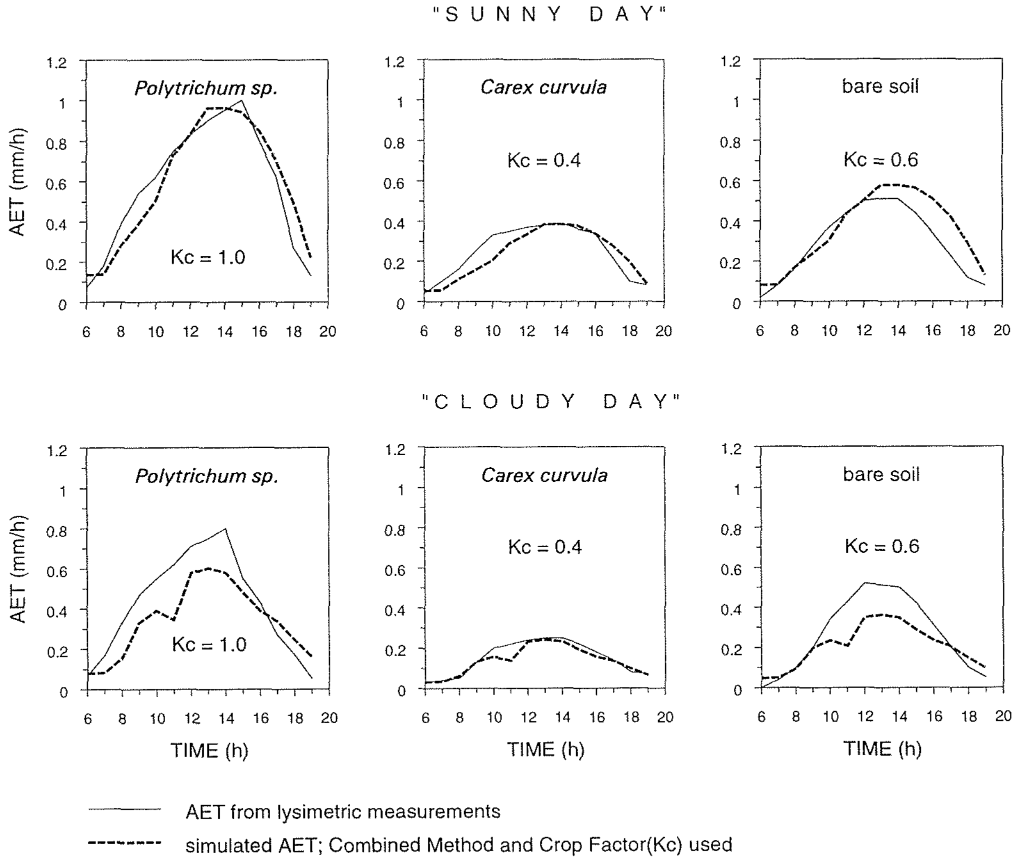

Fig. 4 Calibration of the crop coefficient (*Kc*) by means of lysimetric measurements (Körner, 1978) for a “sunny day” and a “cloudy day” (both averaged over the summer of 1976).

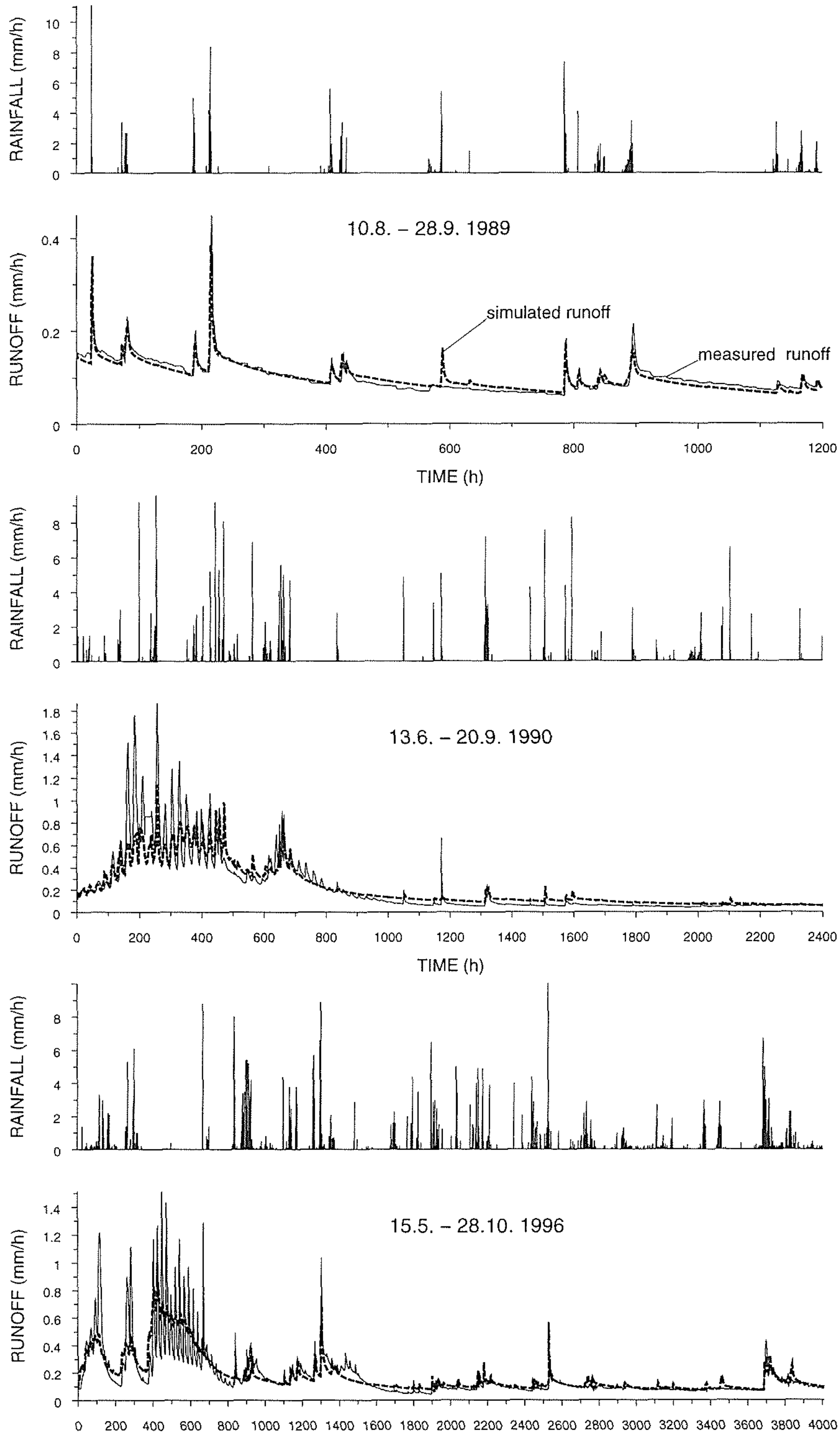

Fig. 5 Time series used to calibrate the model to the Glatzbach River basin (10 August–28 September 1989) and time series used to evaluate the parameter calibration (13 June–20 September 1990 and 15 May–28 October 1990).

calibration, which was derived in the above-mentioned manner, was evaluated against the time series of measured runoff for the years of 1990 and 1996 (Fig. 5).

RESULTS AND DISCUSSION

The generalized TOPMODEL version provided good results on an hourly basis. In particular, the matching of peak flows in the summer months was very good. The model was relatively easy to apply because the number of parameters which have to be calibrated was kept low. Additional parameters to the original version of TOPMODEL such as the Green & Ampt soil parameters and the crop coefficients could be derived from sprinkler experiments and lysimeter measurements respectively so that these parameters have not to be calibrated. Even though the time series used for calibration was very short (50 days) the model provided efficient results in the years 1990 and 1996 which have been employed to evaluate the model adjustment (Table 1).

Table 1 The efficiency of the model and some discharge criteria (all in mm) of the examined years.

Time series	10 Aug.–28 Sept. 1989	13 June–20 Sept. 1990	15 May–28 Oct. 1996
Efficiency	85%	80%	69%
Precipitation	178	386	815
Measured runoff	120	517	694
Simulated runoff	119	523	704
Simulated surface runoff	6	68	81
AET	30	110	247
Calculated snowmelt	0	524	700

During the snowmelt season the model was less successful in simulating the short-time fluctuations of the hydrograph. The authors assume that this limitation in the short-time scale is due to the simplifications of the Degree-day Factor Method which takes the air temperature as an index for all effective factors (such as solar radiation and air humidity) to snowmelt processes.

However, by means of the present simulations TOPMODEL seems to be well suited to the Hohe Tauern mountain range. Beyond that additional adjustments are suggested, which may improve the fitness of the model to the Glatzbach River basin:

(a) Computation of snow accumulation so that the model can be run over several years.

(b) Inclusion of solar radiation, which is now measured within the basin, as a factor relating to evaporation and snowmelt.

(c) Consideration of spatially transition between rainfall and snow within the basin as this can be observed even in the summer months.

(d) Because of freezing phenomena within the upper soil layers, which result in aerial occurring surface runoff for the most part of the snowmelt season, a seasonal variation of the relevant soil parameters should be tested.

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