Spatially Distributed Model Approaches to Hydrologic Processes and River Flow from Mountainous Regions

J. Gurtz, A. Baltensweiler, H. Lang and J. Schulla
Department of Geography, Hydrology Section,
Swiss Federal Institute of Technology Zurich,
Winterthurerstr. 190, CH-8057 Zurich, Switzerland

Abstract

As a result of the pronounced topography, river basins in mountain regions are characterised by strong three-dimensional variations of all land surface features - soil type, soil depth, vegetation - and of all meteorological elements. In the assessment of possible impacts of climatic variations on the water flow and on water resources, a model has to be employed which takes account of these spatial variabilities.

A river basin model was developed for the whole alpine/pre-alpine basin of the river Thur/Andelfingen (1,703sq.km.) and the 12 sub-basins. These basins are located in the north-eastern part of the Swiss portion of the Rhine basin and have an elevation range from 350 to 2,500masl. A considerable part of the Thur basin is high mountain terrain, some of it above the tree-line: much of the basin is under snow cover during the winter season.

In the hydrologic distributed modelling presented here, the digital terrain model (DTM) and land use information, as provided by a geographic information system (GIS), were introduced based on the principle of hydrologic sub-areas (hydrotopes), the assumption being of hydrologically similar behaviour within these hydrotopes. For the spatial interpolation of the meteorological input variables, various methods were employed. The structures of the model components for snow accumulation and melt, interception, soil water storage and uptake, evapotranspiration, runoff generation, and flow routing are described, including a discussion on assessing the time dependency of the various parameters.

The results for each of the hydrologic components are presented with respect to the different sub-areas and altitudinal zones.

Introduction

River basins in mountain regions, together with their typical topographic structures, are characterised by strong areal variations of land surface features, including soils and vegetation. The driving forces behind these variations are the combined effects of geomorphological and meteorological-climatic processes. The corresponding hydrological system of such regions reflects this complexity in the great areal variation of its specific processes. Consequently the modelling efforts directed towards the hydrological components of a mountain river basin need to take account of these particularities of mountain systems; namely,

(a) in the attention paid to vertical and horizontal structures when developing the model components,
(b) in the selection of an appropriate spatial resolution,
(c) and in the required temporal resolution of the model simulations, which much depends on the specific purpose of the model.

In addition, the sophistication of the representative river basin modelling depends largely on

- the availability of information on the spatial characteristics of the basin needed to decide a reasonable spatial resolution, the determination of parameters, and initial values in the model experiments and
- on the existing meteorological networks and data, including their quality and their temporal and spatial resolutions.

The use of geographic information systems that included digital terrain models, as well as the easy access to the data archives of automatic meteorological and hydrometric networks (University of Zurich, Swiss Meteorological Institute, and Swiss Hydrological Survey), offered very favourable preconditions for the present project.

The aim of the project was the continuous model simulation of river flow in the Thur River basin (Fig. 1), which is a 1,703sq.km. pre-alpine-to-high alpine catchment in the north-eastern part of the Rhine River basin of Switzerland. The model simulation includes all important components, such as evapotranspiration (ET) and soil moisture, in their temporal and spatial variations, and in their reaction to meteorological variations. It was also intended to develop the model components with close consideration given to the areal distribution of the hydrological processes (Gurtz et al. 1996).

The River Basin of the Thur

The River Thur/Andelfingen is 127km long and drains a basin from 2,503masl (Santis) down to the reference gauging station of Andelfingen at 356masl, with a mean altitude of 769masl and a mean slope of 7.5 degrees.

The geological formations consist of conglomerates, marl, and sandstone of middle-to-low storage capacity and conductivity. Groundwater resources predominantly exist in areas with a coverage of morainic layers.

The break down of land use is: 57 per cent grassland and agricultural fields, 26 per cent forests, four per cent fruit trees, eight per cent urban areas, and approximately one per cent bare rock. The rest is open water and bushes.

The basin is sub-divided into 12 sub-catchments covering areas between 3.3 and 406sq.km.

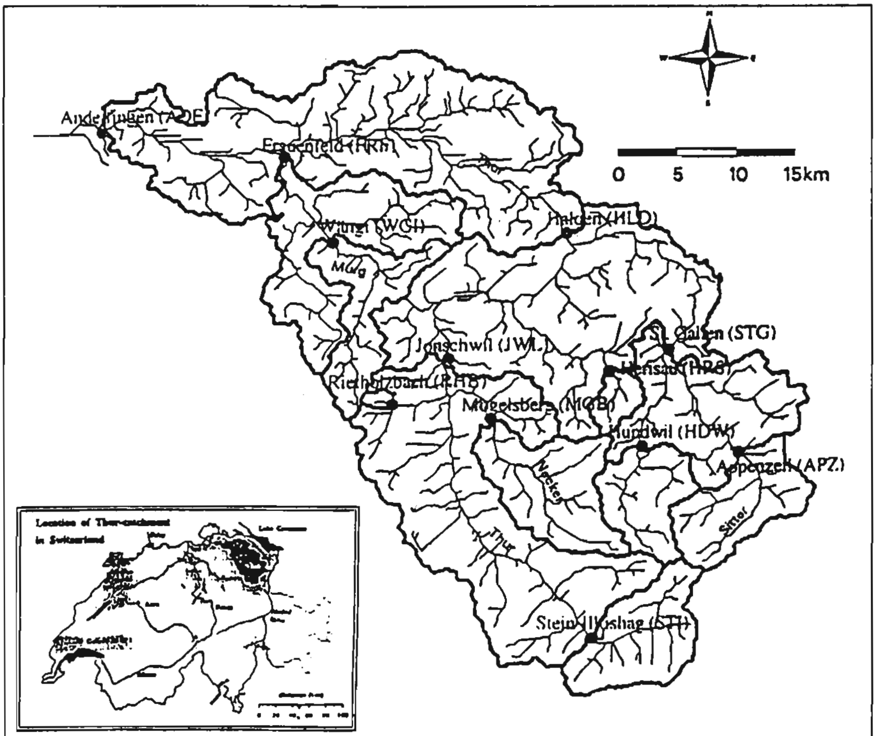


Figure 1: The Thur River Basin and Sub-basins

The official meteorological network of the Swiss Meteorological Institute consists of 12 automatic stations with data teletransmission providing hourly reports. From nine additional climatic stations, three readings per day were available, and the daily values of 42 precipitation stations were used.

Selection of Unit Areas and Scales

Given the purpose of developing the model in connection with catchment characteristics, the requirement of a spatial sub-division of the whole basin into unit areas was obvious. For the application of areal information, a grid-based GIS was available (University of Zurich, Dept. of Geography), offering the possibility

(a) of applying a hydrological model to each grid cell, or
(b) of defining hydrologic unit areas, each of which represent the sum of all grid cells expected to show rather similar hydrological behaviour - to which the model can be applied.

The second approach implies the loss of the individual position of each grid cell; however, with this approach a considerable reduction in computer time is achieved. Under the conditions given in this river basin, a grid size of between 100 to 1,500m was found to be appropriate.

Under this unit area method, the whole basin was structured into five information levels (Nemec 1993).

- The level of the stream system and drainage basin, connected with the topographic level (DTM). It determines the flow lines (channel system) of the various runoff components to the next downstream gauging station.
- The level of the meteorological input variables (precipitation, air temperature, incoming shortwave radiation, vapour pressure, sunshine duration, wind velocity). It serves to delineate the areas of equal meteorological conditions. Each of the 12 sub-basins is sub-divided into elevation zones of 100m equidistance to take into account the various vertical gradients.
- The topographic level is characterised by elevation, aspect, and slope angle. Together with albedo these variables are determinative of the energy available for ET. Each elevation zone is sub-divided into five aspect classes, including horizontal.
- The level of land surface type takes into account vegetation and land use.
- The fifth level includes soil characteristics such as field capacity, soil depth, and conductivity, all important for runoff processes and for ET.

Since land use is to a great extent influenced by soils and topography, and soil itself is related to topography, these factors are not taken into account further in the determination of the hydrological unit areas (hydrotopes). Each hydrotope is thus characterised by the mean values of the contributing grid cells for soil type, slope angle, aspect, and altitude.

A set of parameters and initial values is allocated to each hydrotope, to be processed in the modelling and then connected to the other hydrotopes of the different elevation zones in the drainage basins. The water balance components are then calculated for each sub-basin; with due consideration given to their point of origin, they are used to perform the computation for the basin as a whole.

Blocked off into 100m x 100m grid cells, the whole basin of the Thur/Andelfingen finally was comprised of a total of 2,486 hydrotopes between 0.1 and 2.35sq.km. in area and averaging of 0.68sq.km.

The runoff processes in mountain catchments and their specific dynamics need a high temporal resolution into computational steps of at least one hour or less. On the other hand, soil water uptake by ET is much less variable on a short-time scale and in its effect on the runoff. Therefore this process is sufficiently represented by a daily time step with a corresponding distribution of the amounts at hourly intervals.

The meteorological input variables have to undergo a spatial and, to a certain extent temporal, interpolation procedure, particularly to take into account the altitudinal gradients. For temperature, global radiation, vapour pressure, and wind speed, an empirical altitude relation of the variables was used. In the case of precipitation and sunshine duration, a distance-dependent weighting method or a combination of it and the previous method is employed. This allows even inversion conditions to be treated appropriately.

For each elevation zone an average value of the corresponding values allocated to the grid is determined. The precipitation values are corrected for wind velocity and are different for rain and snow.

Description of the River Basin Model

The model consists of the following main components.

- snow,
- interception,
- soil water uptake and ET,
- soil water storage and runoff generation, and
- flood routing.

The core of the model (Fig. 2) is part of a complex programme system.

Snow Accumulation and Melt

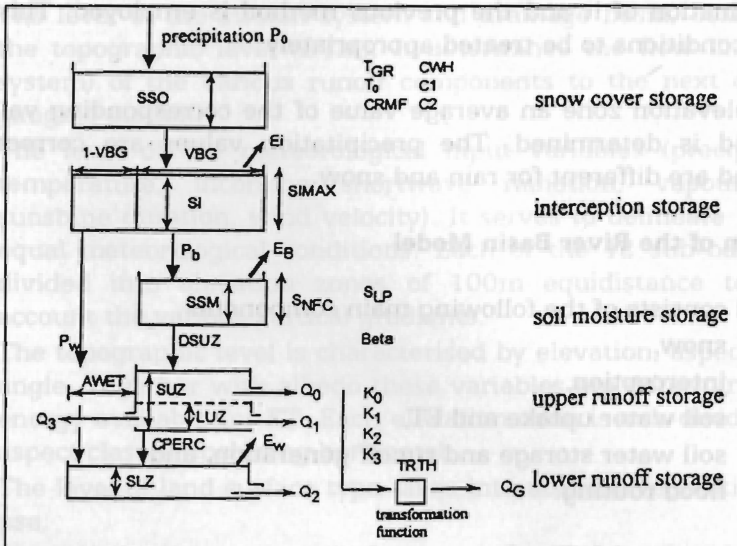
For this component, a combination approach, following Braun (1985) and Anderson (1973), is used based on the temperature-index method and on an energy balance method. Water retention and the refreezing of water into snowpack can be taken into account.

Interception

This model component accounts for interception storage capacities which vary in time and between vegetation species and surface types. Interception and evaporation in vegetated areas are taken only as potential evaporation, as long as there is water in storage.

Evapotranspiration

Particular attention was paid to the ET part of the model, which is based on the Penman-Monteith equation (Monteith 1975) and/or on the Penman equation (Penman 1948; 1956). In the computation of daily values, day-time and night-time hours are treated separately. The parametrisation is mainly based on the Morecs Scheme (Meteorological Office Rainfall and Evaporation Calculation Scheme) after Thompson et al. (1981). The main parameters are: albedo, vegetation height, roof depth, Leaf Area Index (LAI), and stomatal resistance, which are taken as variables in monthly steps. To meet the regional specific altitudinal vegetation gradients, the plant parameters are reduced above 1,300m. As an example, the variable interception storage capacity for various plants is shown in Figure 3. Figure 4 points out an example of variation with time of the LAI for different plant species.



Abbreveations:

AWET	portion of wet areas	P_e	not influenced precipitation
Beta	exponent	P_w	precipitation on the wet area
C1	wind coefficient1	Q_0	quick direct runoff from SUZ
C2	wind coefficient2	Q_1	delayed runoff from SUZ
CWH	water retention capacity of snow cover	Q_2	groundwater runoff
CPERC	percolation to the lower runoff storage	Q_3	karst runoff
CRMF	day-degree-factor	Q_G	total runoff
DSUZ	inflow to the upper runoff storage	Si	interception storage
E_B	soil evapotranspiration	S_{LP}	soil moisture threshold
E_i	interception evaporation	SLZ	lower runoff storage
E_w	wet area evaporation	S_{NFC}	water content of usuable field capacity
K_0	storage constant for Q_0	SSM	soil moisture storage
K_1	storage constant for Q_1	SSO	snow cover storage
K_2	storage constant for Q_2	SUZ	upper runoff storage
K_3	storage constant for Q_3	T_0	threshold temperature for begin of snow melt
LUZ	threshold of SUZ for runoff Q_0	TRTH	translation time
P_b	precipitation below the vegetation	VBG	portion of vegetation covered area

Figure 2: Scheme of the Hydrologic Model (HBVEVA)

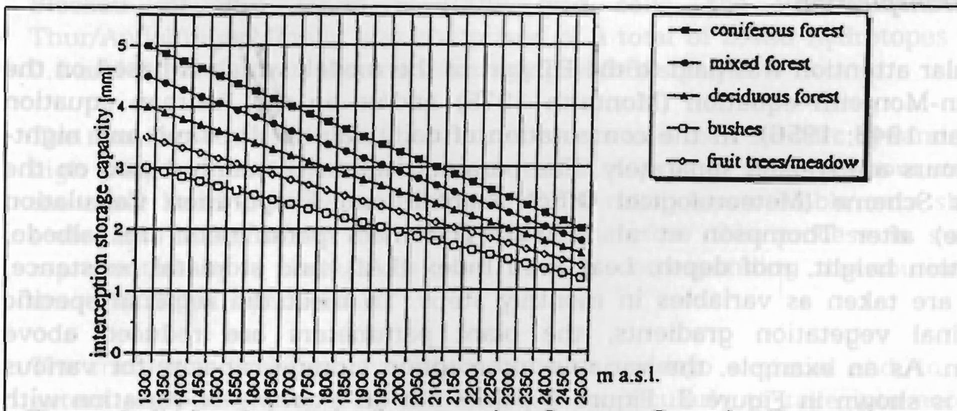


Figure 3: Reduction of the Interception Storage Capacity Depending on Altitude

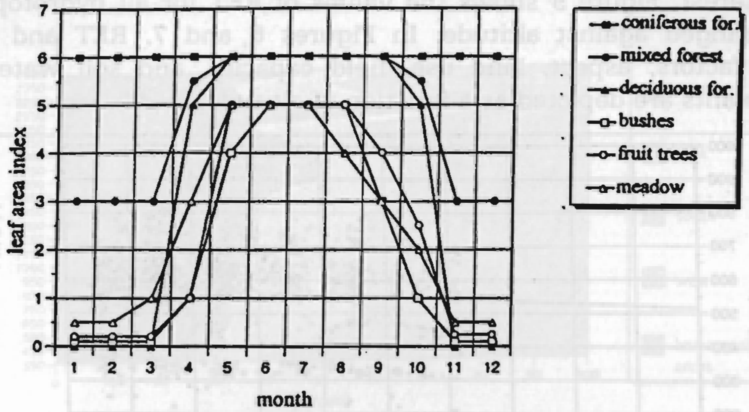


Figure 4: Leaf Area Index (LAI) for Different Species of Vegetation

Net radiation as the forcing element for ET is determined as a function of aspect, slope angle, and albedo, which is dependent on the type of surface.

Soil Water Storage and Runoff

This part of the model is derived from the conceptual HBV-ETH model (Bergström 1976, Jensen 1986).

Results of the Model Simulation

The model computations of the runoff and water balance were performed for all 12 sub-basins for the years 1993 and 1994 based on the areal distributed scheme, and from these results the values for the total basin were derived.

Potential and Real Evapotranspiration

The potential ET (PET) mainly reflects the area distributed energy available for ET. In the lower-to-middle elevations, PET shows values between 550 and 650mm. In the higher elevation zones, the range of PET extends also to values below 550 and above 650mm for reasons of topography and albedo. The annual average value of PET for the whole basin amounted to 589mm.

The corresponding computations for the real ET (RET) provided an average annual value of 506mm. It is remarkable that the maximum difference of 137mm between PET and RET showed up in the highest sub-catchment. The range of variation is much larger for RET than for PET. The minimum RET values are, of course, obtained for settlements and rocky areas. Aspect, land use, and soil water storage capacity are also reflected in RET patterns.

In mountain areas, the vertical gradients of the hydrological components are of particular interest. Figure 5 shows the values of RET for all hydrotopes in the Thur basin ranged against altitude. In Figures 6 and 7, RET and the main determining factors, aspect, land use, field capacity, and soil water content available to plants are depicted as a function of altitude.

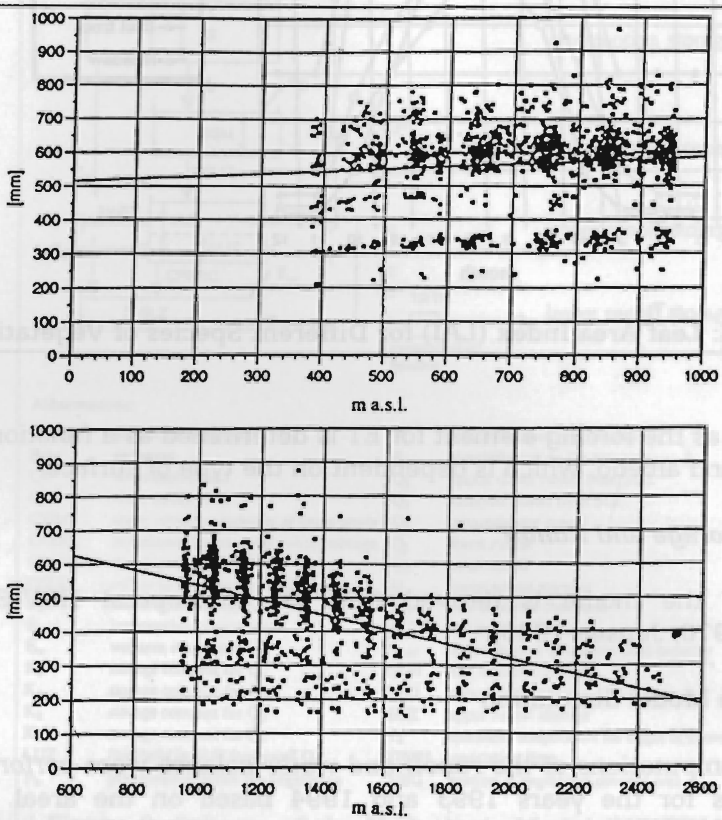


Figure 5: Real Evapotranspiration (RET) for all Hydrotops of the Thur Catchment Depending on Their Mean Altitude

It is obvious that, besides the decrease in the energy available for ET, the field capacity of the soils available to plants is a main controlling factor for the decrease of ET with altitude and for the range of variation within a certain elevation zone. This range of variation with altitude also decreases with elevation, because of the reduction of influencing factors with altitude.

Figure 8 is an interesting comparison of the vertical gradients for the annual computed RET and PET. While the PET values reflect the available energy, including the conditions for aerodynamic diffusion, RET is in addition affected by the soil water availability for plants and surface vapour pressure. In other words, vegetation, soil depth, and snow coverage with its upper limit of maximum saturation vapour pressure at 6.11 hPa at the melting point. Taken together, these conditions produce a zone of maximum RET between 600 and 1,200masl.

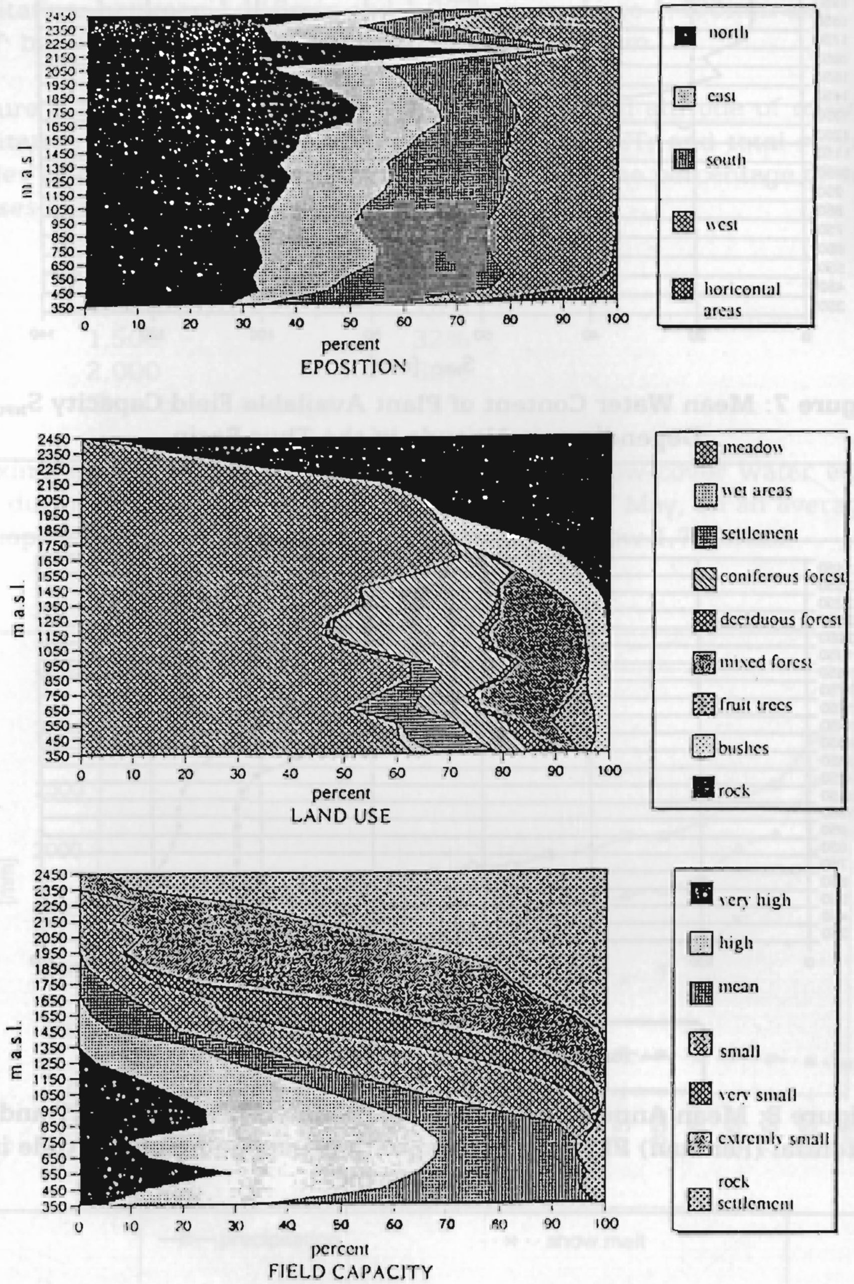


Figure 6: Percentage of Area for the Different Classes of Exposition, of Land Use and of Field Capacity Depending on Altitude

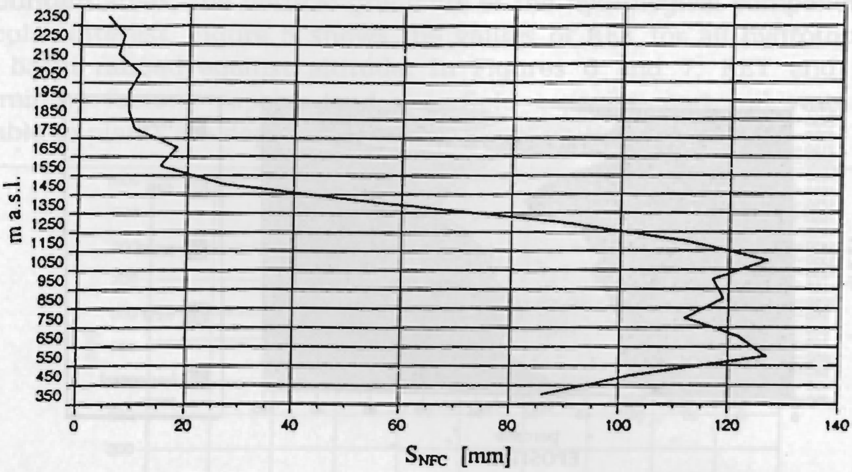


Figure 7: Mean Water Content of Plant Available Field Capacity S_{NFC} Depending on Altitude in the Thur Basin

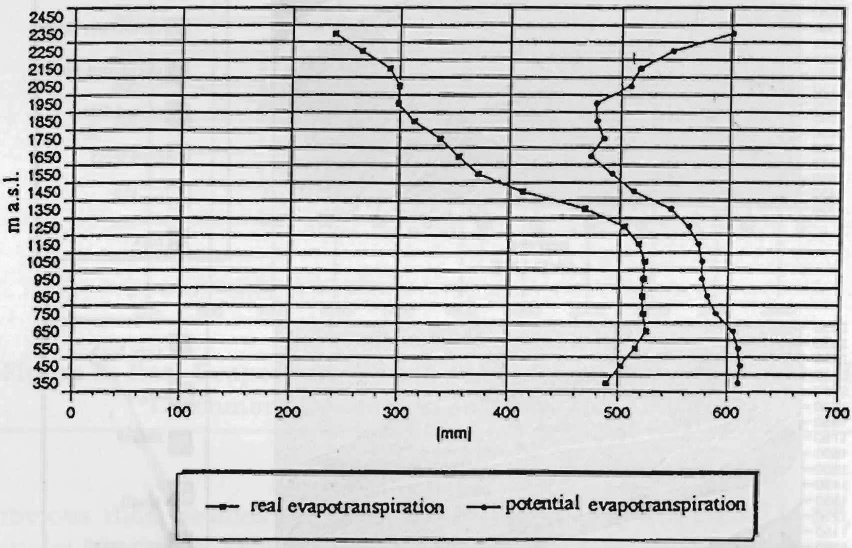


Figure 8: Mean Annual Values of Real (Penman-Monteith) RET and Potential (Penman) PET Evapotranspiration Depending on Altitude in the Thur Basin

Runoff, Snowmelt and River Flow

Average specific runoff increases with elevation for several reasons: increasing precipitation, decreasing soil water capacity, and decreasing ET. The extreme values range from 400mm runoff in the low-level zones of the Thur River to

2,500mm in the uppermost rocky parts of the high mountains. The 12 sub-basins show the following range of specific values:

Precipitation: between 1,116mm and 1,973mm, average 1,460mm and
Runoff: between 593mm and 1,465mm, average 927mm.

In Figure 9 an overview is given of the variation with altitude of mean annual precipitation P; snowmelt; real evapotranspiration, RET; and total runoff, R. In altitudes below 500m, snow coverage is rather rare. The percentage of snow in P increases at the following rates.

masl	P_{snow}/P_{total}
1,000	18%
1,500	32%
2,000	60%
Thur basin average	13%

Approximately 45 per cent of the melting of the snow-cover water equivalent occurs during the time after 1 April, and by the end of May, on an average, snow has disappeared completely in the elevation zones below 1,700masl.

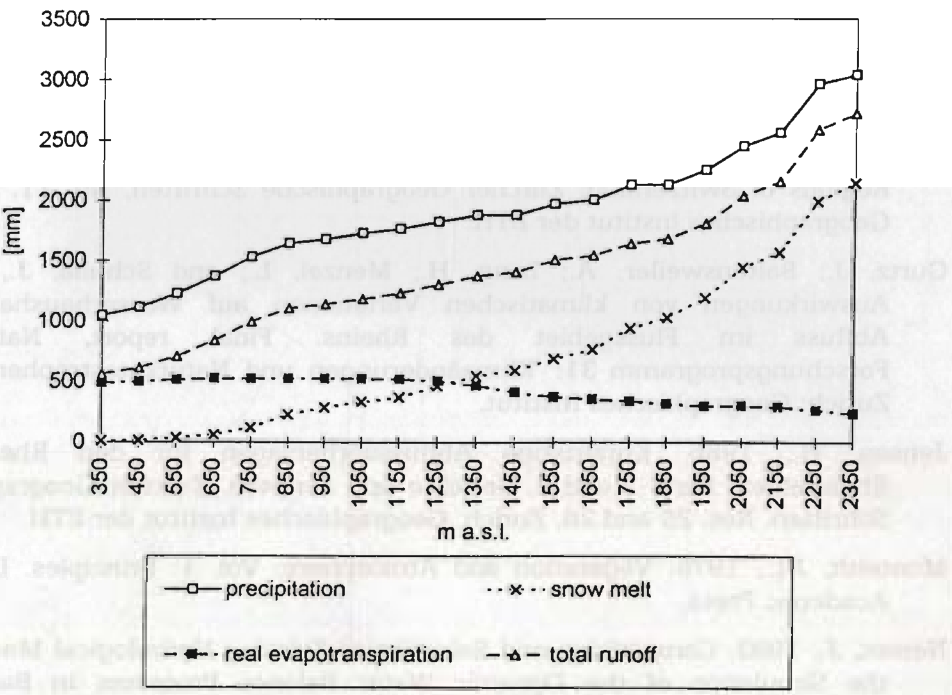


Figure 9: Mean Annual Values of Precipitation, Snow melt, Real Evapotranspiration and Total Runoff Depending on the Altitude in the Thur Basin

Conclusions

1. It is important to work with a spatial catchment sub-division into hydrologically similar areas (hydrotopes), or grids, for more accurate calculations in mountainous areas. A grid cell size of between 100xl00m and 1500xl500m is found to be optimal.
2. Spatial and temporal distributed values of model parameters are needed.
3. The sub-models for soil moisture estimation, soil moisture extraction by evapotranspiration, and runoff formation are of major relevance for more accurate model simulations of the water balance and streamflow.
4. A careful selection of the snowmelt sub-model and its parameters is very important for precise runoff simulations in mountainous regions.

Acknowledgement

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