Estimation of Hydrological Balance Components under Variable Conditions of Mountainous Catchments

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Abstract

The basic water balance components were studied in the mountainous catchment of Jalovecky Creek, Slovakia, in the hydrological years 1989-1994. Monthly precipitation totals were measured by six storage gauges. Runoff was measured at the catchment outlet. The main attention was given to the modelling of actual evapotranspiration. The SOIL model was used in the study. Calibration of the model was based on field measurements of soil moisture, soil temperature, and spruce tree transpiration. A sensitivity analysis revealed that the relative air humidity and leaf area index (LAI) were the most important parameters influencing evapotranspiration modelling. The main soil parameters (saturated conductivity, wilting point, porosity), on the other hand, had not much significant influence on the calculated value of actual evapotranspiration. Consequently, the regionalised average soil hydraulic characteristics seem to be applicable by water balance calculations. Subdivision of the catchment into six quasi-homogeneity elementary areas was accomplished by transformation of point monthly precipitation and actual evapotranspiration data into catchment-related values, which were used in the analysis of water balance. This analysis showed that the modelled values of actual evapotranspiration were reasonable. A description of precipitation, runoff, and actual evapotranspiration regimes provided the basic information on catchment hydrology and the regime of catchment water storage.

Introduction

Mountainous areas, chiefly owing to their topography and related dynamics, are far more ecologically sensitive than lowland and upland areas. Under the conditions of the mountainous catchments in the upper parts of the Carpathians, where atmospheric precipitation is the exclusive source of water, the need for proper knowledge of the whole complex of the hydrological cycle arises. The importance of detailed, accurate, and theoretically based quantification of water balance components is permanently growing due to demands for water resources. This paper describes the approach used for water balance calculations in the experimental mountainous catchment of Jalovecky Creek (Western Tatra Mountains, Slovakia) in the hydrological years from 1989-1994. Special attention is given to the calculation of the evapotranspiration component and the sensitivity of the applied model to different parameters and input data. The experience with estimates of areal precipitation over topographically complex terrain is briefly mentioned, and the results of the water balance are analysed at the end of the paper.

Catchment and Data

The Jalovecky Creek catchment is situated in the Western Tatra Mountains, which form the highest part of the 1,200km-long chain of Carpathian Mountains. The altitudes range from 800 to 2,178masl; the mean altitude is 1,500masl. The main part of the catchment (93%) is made up of Paleozoic granitoids and crystalline schists, the rest being formed mainly by Mesozoic limestone and dolomite. The forest cover, consisting predominantly of spruce, accounts for approximately 44 per cent of the total catchment area. The rest is covered by dwarf pine (32%), alpine grass meadows, and rocks (24%).

The soil cover is characterised by Dystric Cambisols from weathering products of acid rocks at the lower parts, Spodo-dystric Cambisols and Ferro-humic Podzols from lighter textured weathering products of acid rocks, and Ranker and Dystric Lithosols at the highest altitudes. Leached Rendzinas or Calcic Cambisols from weathering products of solid carbonate rocks are located on the Mesozoic complexes.

Hydrological research in the catchment started in 1986. Runoff was measured by a gauge situated at the catchment outlet (800masl). Monthly precipitation was measured by six storage gauges situated at altitudes of 750, 1,100, 1,400, 1,500 (2 gauges) and 1,775masl. Air temperature was measured continuously at altitudes of 570, 750, and 1,500masl. Additional data were measured by two data loggers at 1,100 and 1,500masl.

Determination of the Basic Components of the Water Balance Equation

The main problems of water balance calculation in mountains are connected with **measurements** of basic components of the water balance equation in harsh climatic and topographical conditions, on the one hand, and estimation of their **representative areal values** on the other hand. For the latter problem we subdivided the whole catchment into six areas affiliated to particular storage gauges. Altitude, vegetation, soils, and other important geographical features were taken into account in the differentiation process. These elementary areas are considered to be quasi-homogeneous with regard to soil, vegetation, and climatic parameters.

Runoff

Since runoff was measured at the catchment outlet, there was no need for calculation of a representative areal value. It was also assumed that hydrological and hydrogeological water divides were identical.

Precipitation

It is generally supposed that the spatial variation of precipitation in mountainous catchments is very high. Our experience shows that the differences between precipitation at the lowest altitude (750masl near the catchment outlet) and the remaining storage gauges (1,100-1,775masl), which were situated in mountains, are much higher than the differences among particular gauges in the mountains. However, the locations with preferential wind flow exhibited extreme measured values under certain conditions, especially at the end of winter. This highlights the need for a suitable installation of the gauge in the field with respect to the area it should cover and to terrain configuration. Our measurements also showed that the increase of precipitation with altitude was not linear.

Methods like the division of catchments into sub-catchments, Thiessen polygons, weighted averages, krigging, co-krigging, and trend surface analysis can be used for the transformation of point-related data to area-related ones. Small mountainous catchments do not usually have enough data for application of the complex transformation methods. Several simple methods for estimating areal precipitation were used in the Jalovecky Creek catchment, including the arithmetic mean, Thiessen polygons, altitude gradients (described by linear regression equations), and the method of altitude zones chosen with respect to precipitation patterns in the catchment. The results show that the differences expressed in percentages from the values calculated by the last method are not very high, although the first two methods are generally not recommended in topographically complex terrain (Table 1).

Table 1 Average Deviations [%] of Areal Precipitation Estimates Calculated by Different Methods from the Results Given by the Method of Altitude Zones in the Hydrological years 1989-1994: A arithmetic mean, B thiessen polygons, C altitude gradients (linear regression)

	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX	X	Year
A	-3	-7	-3	-6	-3	-6	-6	-3	-4	-1	-3	-1	-4
B	1	0	3	-1	3	-1	-2	0	0	5	2	1	1
C	5	-1	6	0	4	2	2	-1	1	7	6	3	3

Considering the possible measurement errors, the differences between particular methods are almost negligible, especially for the yearly means. The arithmetic mean gives systematically lower areal estimates, while Thiessen polygons give very similar results to altitude zones. Altitude gradients give higher areal estimates. For further processing, the method of altitude zones was chosen to calculate catchment mean precipitation.

Evapotranspiration

Estimation of catchment evapotranspiration causes the greatest problems. Our lack of knowledge of evapotranspiration is due to scarcity of instruments able to measure evapotranspiration accurately under all weather conditions. Calculation of evapotranspiration from the water balance equation is not suitable for small catchments and temporally short data sets. For this reason, the modelling of evaporation received special emphasis. The modelling procedures typically include soil water movement, vegetation demand, and evaporation from soil surface, as well as intercepted precipitation including dew formation. These models depend typically on an adequate description of the physical characteristics of the land surface and vegetation. The soil water flow is characterised by water retention curves and functions for saturated as well as unsaturated hydraulic conductivities. Vegetation properties include parameters describing the functions of plant aerodynamic and stomatal resistances (Tattari 1994).

Modelling of Evapotranspiration

In this study, a one-dimensional SOIL model (Jansson 1991) was used to simulate the daily values of water content in each soil layer, soil temperature in the upper layer, and water loss due to evaporation and transpiration in the mountainous catchment forested mainly by spruce.

The basic structure of the model is a depth profile of the soil in which two coupled differential equations for water and heat flow are solved. The most important functions covering the soil water flow include determination of the water retention curve and unsaturated hydraulic conductivity. Evaporation can occur as transpiration and root water uptake, soil surface evaporation, or evaporation of intercepted water. Reduction of transpiration occurs when the soil dries and when it cools down. The model normally uses a complete set of standard meteorological data as input data, but it can be run using only air temperature and precipitation, too.

Since the SOIL model is a one-dimensional soil-vegetation-atmosphere model, the catchment was divided into six quasi-homogenous areas, as was mentioned above. The data sets with the input variables and parameters were prepared for each area, and the calculated actual evapotranspiration was transformed into a catchment areal value using the same approach as by areal precipitation.

The initial state variables (soil temperature, soil moisture) were based on field measurements. The input driving variables used in the simulations were daily air temperature and precipitation. Wind speed, air humidity, and cloudiness were not measured continuously during the whole studied period in the catchment. Therefore, they appeared as parameters representing average annual values at elementary areas, having been derived from meteorological studies in the Tatra Mountains as well as from meteorological measurements at the Experimental Hydrological Base.

Analysis of SOIL Model Parameters

The sensitivity of the SOIL model was tested during our study and also reported in numerous publications. Critical to the calculation of evapotranspiration is a simple definition of the hydrologically significant vegetation properties. If the basic biome type (forest, grassland, crop, etc) can be defined and general physiological controls are assumed for it, then the most important general vegetation parameter needed is the leaf area index (LAI). LAI is used to define vegetation variability across the landscape. Consequently, evapotranspiration is proportional to LAI, although not linearly so. We have performed calculations under the SOIL model, with LAI values changing from 1 to 5, and then analysed the changes of average annual evapotranspiration and its components. The leaf area index had the most significant influence on actual evaporation of intercepted water.

Knowledge of soil characteristics and properties is very important for modelling soil water balance. The PLOTPF programme, which is part of the standard SOIL model package, was used to calculate soil properties according to the soil particle size distribution, porosity, and humus content. This programme was developed for the selection of input data to the SOIL model, modification of soil properties, and estimation of coefficients in the Brooks and Corey expression of the water retention curve. The necessary input data were obtained from an analysis of soil samples collected in the experimental catchment as well as from the published data from similar mountainous regions. A sensitivity analysis indicated that rather significant changes of the main soil parameters (saturated conductivity, wilting point, and porosity) are influencing the calculated value of actual evapotranspiration very little. Therefore, the regionalised average soil hydraulic characteristics derived from the limited number of soil samples collected in the Jalovecky Creek catchment seem to be applicable to the water balance calculations.

Field Measurements Used for Model Calibration

Field measurements of soil moisture, soil air temperature, and spruce tree transpiration were used to calibrate of the model. The time domain reflectometry (TDR) technique was applied to the monitoring of soil moisture. Soil moisture measurements were performed in the layers 0 - 30cm and 30 - 60cm at two sites by data loggers. The comparison of measured data and calculated values of soil water content for selected periods is shown in Figure 1.

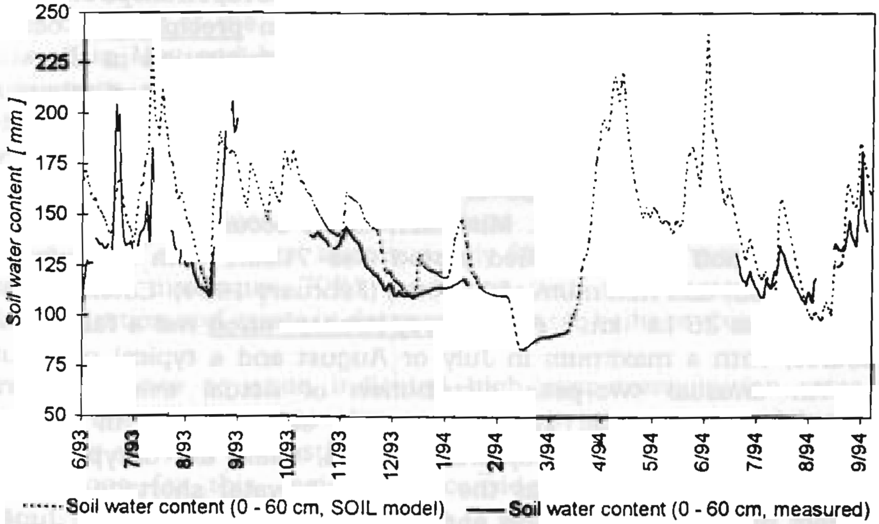

Figure 1: Comparison of Measured Soil-water Content in the 0 – 60cm Layer and the Soil-water Content Calculated by SOIL Model

The heat balance method (Kucera et al. 1977) was applied to measure the amount of transpiration of the selected spruce tree within the representative plot located at an altitude of 1,070masl. (Molnar and Meszaros 1994). The subject plot was centrally positioned within the catchment, the comparison of measured and modelled transpiration for which is shown in Figure 2.

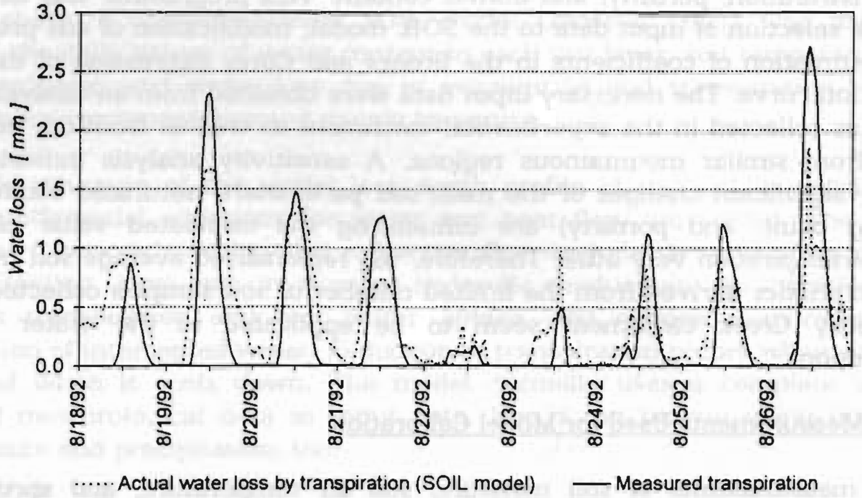

Figure 2: Comparison of Transpiration Water Loss Calculated by SOIL Model and Measured Transpiration by Head Balance Method

Analysis of Catchment Water Balance

The annual regime of precipitation, runoff, and actual evapotranspiration during the studied period is shown in Figure 3. Maximum <u>precipitation</u> occurs in summer; the minimum in winter. Mean monthly precipitation in the studied period was 120mm, with a maximum of 312mm (August 1990) and minimum of 23mm (untypically in the extremely dry August of 1992). Winter precipitation is accumulated in the catchment in the form of snow cover, typically between November and March. The release of this storage in April and May causes maximum <u>runoff</u> in these months. Minimum runoff occurs usually in February. Mean monthly runoff in the studied period was 71mm, with a maximum of 254mm (May 1992) and minimum of 11.1mm (February 1994). Catchment mean specific runoff was 26 $l.s^{-1}.km^{-2}$. <u>Actual evapotranspiration</u> has a fairly uniform annual course, with a maximum in July or August and a typical minimum in February. An unusual two-peak distribution of actual evapotranspiration occurred in the hydrological year 1992. The second peak in September represents the usual value of evapotranspiration, while the untypically small actual transpiration in August was the result of a water shortage due to the coupled effect of little precipitation and high evapotranspiration in June and July. The mean monthly evapotranspiration calculated for the studied period was 48mm, with a maximum ofs 112mm (August 1993) and a minimum of 7mm (February 1994).

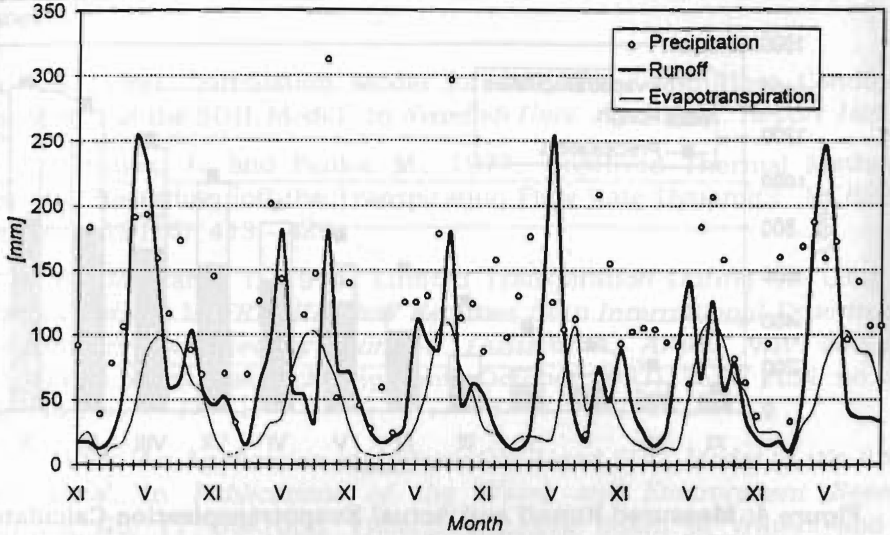

Figure 3: Monthly Precipitation, Runoff and Actual Evapotranspiration (calculated by SOIL model) in Hydrological Years 1989-1994

A knowledge of precipitation, runoff, and evapotranspiration regimes provides not only the first information on catchment hydrology but an idea of the accumulation and release of catchment water storage as well. Accumulation and release of water stored within the catchment are among the factors that determine the behaviour of catchment ecosystems. Considering the mean monthly data from the hydrological years from 1989-1994, water storage in Jalovecky Creek catchment increases from November until March. A small decrease in April is followed by rapid drops from May to June, when the storage drops by one-half of the previous month's storage. This phenomenon reflects high runoff in May and high actual evapotranspiration in June and July. The rapid decrease of water storage ceases in August, on account of maximum summer precipitation and the decrease of actual evapotranspiration in the autumn. Inputs and outputs from catchment water storages are balanced at the end of the hydrological year in October. This process is seen in Figure 4 which shows cumulative values for the average hydrological year. According to calculated runoff coefficients, approximately 60 per cent of precipitation runs off (minimum 53, maximum 70%), and the rest represents the amount of evapotranspiration and errors in determining water balance elements.

The water balance equation indicated high evapotranspiration rates in the catchment. These rates were also confirmed by the SOIL model simulation. These results are very interesting, since the values of evapotranspiration stated in publications for this region are considerably lower. Higher values of evapotranspiration indicate the necessity to better understand the role of forests in the mountainous catchment.

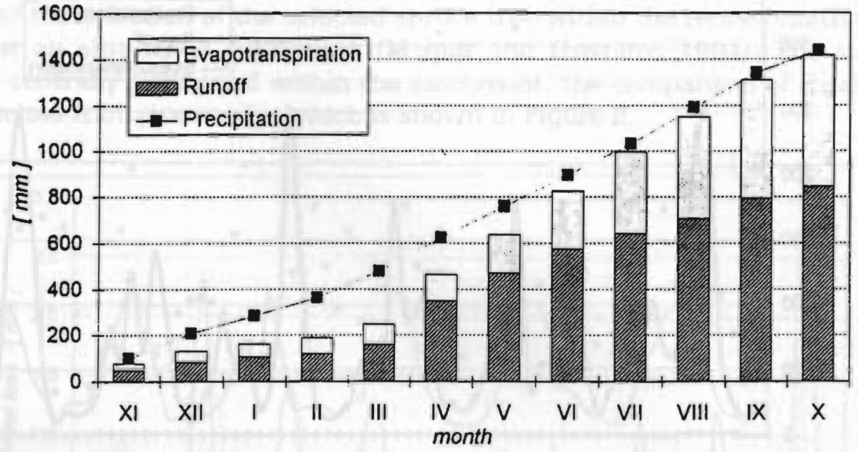

Figure 4: Measured Runoff and Actual Evapotranspiration Calculated by SOIL Model Compared to Measured Precipitaiton; Average Cumulative Monthly Values from the Period 1989-1994

Conclusions

The concept of sub-division of a catchment into partial areas for calculating evapotranspiration and other water balance components forms the basis of understanding the catchment´s processes. Due to the spatial variability of catchment characteristics (soils, cover, topography), different areas play different roles in the total catchment behaviour. As the basic laws of water movement and mass and energy conservation are the same in mountainous as they are in all other areas, the crucial problem seems to be the reliable determination and generalisation of hydrometeorological input variables and parameters characterising soils and vegetation under the highly variable conditions of mountainous catchments.

Physically based deterministic models, using the laws of energy, mass, and momentum conservation, can be used to calculate water balance in mountainous catchments with reasonable results. Since such models also generally contain non-measurable parameters, the values of these parameters must be determined on a more subjective basis or taken from already established knowledge. In addition, the variables that represent spatial and/or temporal averages are difficult to measure over the complete catchment area.

The need for vegetation characteristics arises. The use of remote-sensing techniques for determination of the leaf area index, surface temperature, and other parameters is now common. Utilisation of satellite images by parametrisation and arealisation in lowlands and agricultural areas is well established, but a lot of work has yet to be done in mountainous forested areas.

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