Estimation of Mean Annual Water Balance Components in a Midland Catchment

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Abstract

The objective of the paper is to estimate the mean annual water balance components in a midland catchment using a simple methodological approach. The method of calculation is based on the information obtained by sub-dividing the study catchment into a grid network. For each grid point the elevations in above mean sea level (amsl) were estimated from the topographic map and the mean annual precipitation from the isohyet map. With the relationship established between the elevation of grid points and the annual percentage of precipitation corrections for each grid point, the corrected mean annual precipitation was calculated. The same technique was used for calculating the mean annual temperature and mean annual potential evapotranspiration. Then the mean annual actual evapotranspiration was calculated for the uncorrected and corrected mean annual precipitation and potential evapotranspiration at each grid point. From all grid points the average uncorrected and corrected annual precipitation and areal actual evapotranspiration were calculated. The annual runoff component was computed from daily limnograph measurements, the soil moisture content for the long-term water balance being neglected. The obtained results show that the use of a simple method is possible for the indirect calculation of the mean annual uncorrected and corrected precipitation, actual evapotranspiration, and mean annual runoff as components for water balance estimations in a midland catchment.

Introduction

Accurately estimating water balance is a basic hydrological problem, especially for mountainous or midland catchments. Molnar et al. (1990) analysed the problems by determination of water balance components (precipitation, runoff, evapotranspiration, and water storage) in mountainous catchments in a typical Carpathian region. The methodological approach for determining water balance components in a midland catchment is based on a topographic map of the analysed catchment being sub-divided into 4 x 4km grid fields. The numeration of the grid points is based on the paper by Mendel and Golf (1990). The elevations in amsl were estimated for each grid point from the topographic map. The measured precipitation at rain gauge stations situated in the catchment is subject to systematic errors of measurement. Estimation of the precipitation measurement errors and application of the correction methods is another current problem in the study of water balance under various conditions. Many scientists in numerous countries are engaged in this problem. Such activities in Slovakia have been reported by Mendel and Pekarova (1983), Lapin (1990), Lapin et al.

(1991), Mendel and Pekarova (1995), and other authors. This problem was also researched in the International Hydrological Programme, and the results are described by Puskas et al. (1984). In general, precipitation as measured by existing rain gauges is influenced by water losses due to the wetting of the rain gauge, by evaporation from the rain gauge, and by aerodynamic factors (wind effect). We can find a method for calculating these systematic measurement errors of precipitation components in Puskas et al. (1984) and Mendel and Pekarova (1995). The correction errors of precipitation measurements for each month in the time interval 1976 - 1980, and also for seasonal and annual time intervals in the analysed years, were calculated by the method of Mendel and Pekarova (1983) for daily measured precipitation at six rainfall stations situated in the territory of Slovakia at elevations of from 131.2 to 1,780masl. From the obtained results, at different elevations, the relationships between the altitude of rain gauge installations in masl, and the percentage of monthly, seasonal, and annual precipitation corrections were calculated. For each grid point in the study catchment, the percentage of precipitation corrections and the corrected precipitation amount were also calculated, as was, at all network points, the mean areal annual uncorrected and corrected precipitation. The relationship between the mean annual temperature and the different elevations was estimated by Mendel and Golf (1990) using data from 36 meteorological stations on the territory of Slovakia. The mean annual potential evapotranspiration was estimated using the method described by Novak (1994, 1995), and the mean annual actual evapotranspiration was determined by the method described by Babkin and Vuglinskij (1982) and also by Novak (1994, 1995). According to Miklanek (1994a) the dependence of evapotranspiration on elevation has a different character and can be estimated as a gradient from measured evaporation data, in an inverse exponential relation, by application of the hypsographic curve, or mean catchment elevation, and by application of relative daily or seasonal courses at different elevations. In our case the relationship between the potential evapotranspiration and the elevation was applied for each grid point in the study catchment. According to Lang (1981) and Miklanek (1994b), present knowledge about the mean annual evapotranspiration in mountainous catchments based on conventional water balance estimates suffers from inaccuracies in the determination of precipitation. The vertical gradient of evapotranspiration given by different authors and regions ranges from 71 to 356mm of decrease for each 1,000m of increase in altitude. Generally precipitation increases with altitude. Molnar et al. (1990) reported that the annual gradient of precipitation is equal to 86mm per 100m of catchment elevation. For the territory of Slovakia, the mean annual evapotranspiration gradient is a 260mm decrease for every 1,000m increase in altitude. According to Mendel and Golf (1990), the annual temperature gradient on the territory of Slovakia also decreases by 0.5°C with each 100m increase in altitude. The soil moisture content can be neglected for a long-term water balance calculation. For a short-term interval, for example monthly, it is possible to estimate the soil moisture using a method proposed by Kostka (1992) for determining water content in the root zone of a soil profile in a mountain or midland catchment. The principle is based on the calculation of the potential evapotranspiration by the climatological mean method described by Miklanek (1991) and by use of the linear root constant regulating function producing the soil-water content in mountain or midland catchment. Kostka (1995) presented another way of estimating soil moisture content and its spatial distribution in the root zone using a GIS method, namely, its capability of modelling spatial interrelations. The computation process was applied in an experimental catchment in the western Tatras. Miklanek (1995), by studying the monthly sums of potential evapotranspiration for ten stations on the territory of Slovakia over a 25-year period (1956-1980), found that the relative annual courses of potential evapotranspiration lend themselves to approximation by a normal distribution curve and also found that its parameters are linearly dependent on the elevation. According to Miklanek (1995) the parameters can be indirectly determined using linear regression. On the basis of the normal distribution function with its parameters applicable to our catchment, we can determine the monthly potential evapotranspiration indirectly by way of the estimated mean annual potential evapotranspiration. If we wish to calculate the monthly uncorrected and corrected precipitation, we can also, in principle, estimate the other monthly water balance components. Ding and Liu (1994) reported a methodological approach for estimating water balance using multiple regression equations for the calculation of precipitation in a catchment which was divided into grids of 0.5° by altitude and longitude, which are the central values in the grid. The annual evaporative power was calculated by using the mean annual temperature and precipitation. Xuecheng et al. (1990) have estimated the water balance components in a hill slope catchment using an exponential relationship between runoff and precipitation and potential evapotranspiration and a relationship between the ratio of actual to potential evapotranspiration and the ratio of precipitation to potential evapotranspiration. For the precipitation corrections, a correction, coefficient of 19 per cent was used. In general, we can see that the methods used by Xuecheng et al. (1990), Ding and Liu (1994), Novak (1994, 1995), and Babkin and Vuglinskij (1982) are similar.

Study Catchment

The area of the study catchment, Ladomirka to the Svidnik cross-section is 185.8sq.km. with a mean altitude of 478masl, within the range of from 240 to 550masl. Part of the catchment is used for agriculture (40%) and the other part is forested (60%). The length of the Ladomirka River is 20.2km. The Ladomirka River is a left-hand tributary of the Ondava River basin which is situated in eastern Slovakia. The territory from a geomorphological point of view is a flysh zone, which is characterised by high erosion. The mean annual precipitation from the period from 1965/66 to 1984/85 in the catchment was 789.9mm. The mean annual runoff was 404.1mm, with the specific runoff being 12.7 $l.s^{-1}.km^{-2}$. The mean annual discharge was $2.36m^3.s^{-1}$ and the runoff coefficient 0.51. The scheme of the study catchment is displayed in Figure 1. Precipitation was measured with the standard rain gauge Metra at 4 stations (Vapenik, V. Komarnik, Ladomirka, and Svidnik). The streamflow gauge station was located in the town of Svidnik, where measurements were taken with a limnograph. The evapotranspiration is not available directly from measured data. The water storage component was neglected when computing the annual water balance.

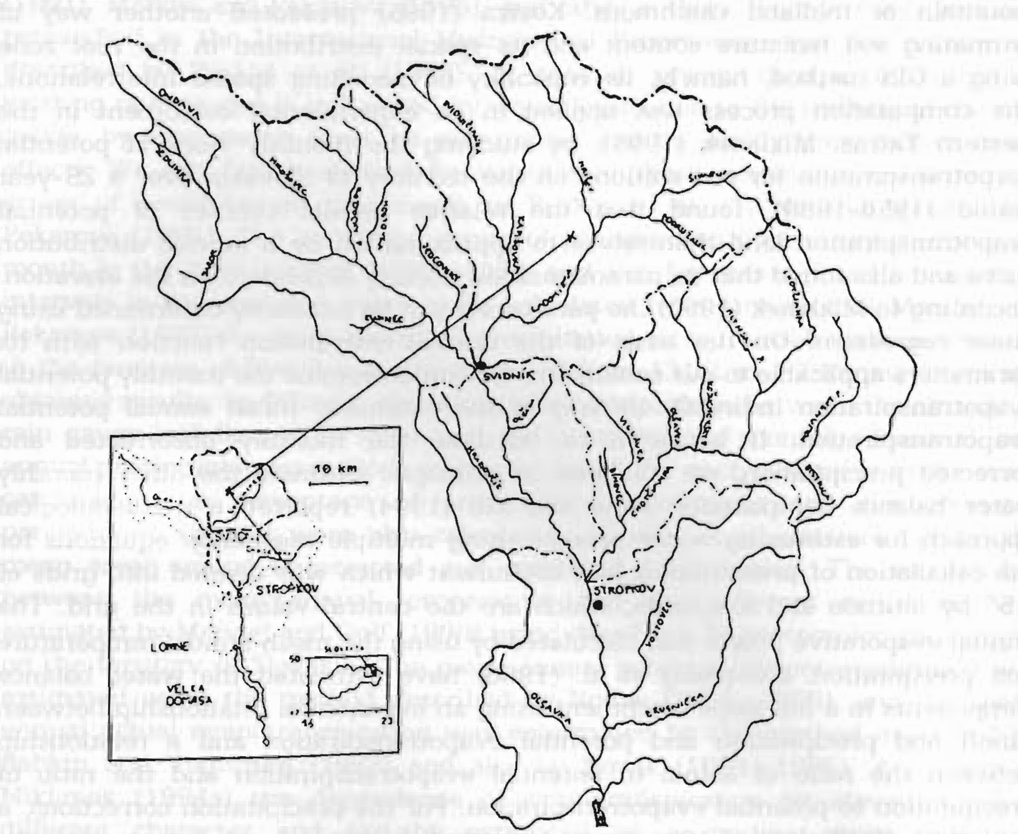

Figure 1: Scheme of Ladomirka Catchment at the Svidnik Cross-section

The Methodological Approach to Estimating the Annual Water Balance

For a particular catchment over a long-term period, the relationship between the basic components of the annual water balance is usually expressed in the form

$$P - R - E = 0 \qquad (1)$$

where,
P is the mean annual catchment precipitation,
R the mean runoff, and
E the mean actual evapotranspiration.

The component of soil moisture storage is neglected for a long-term water balance calculation. In the study of the long-term water balance, the basic problem is the accurate determination of the water balance components by direct measurement or indirect calculation. It is known that the precipitation measurements are point measurements subject to systematic measurement errors. In order to estimate areal precipitation, the study catchment was sub-divided into 12 grid points of 4 x 4sq.km. (Fig. 2).

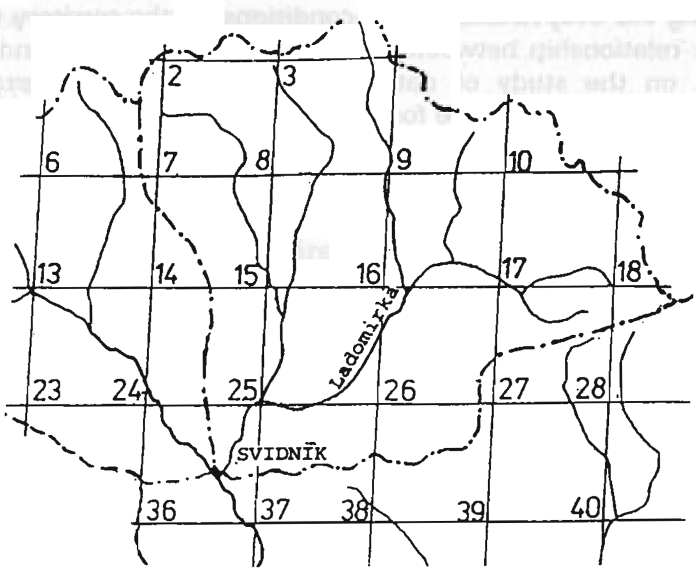

Figure 2: Ladomirka Catchment Sub-divided into a 4 x 4km Grid System

For each grid point the mean annual uncorrected and corrected precipitations were estimated on the basis of the isohyet maps compiled from readings at four rain gauge stations situated in the study catchment. The calculation of the annual correction as a percentage of annual measured precipitation is based on the relationship between the percentage of correction and grid point elevation in masl, in the form

$$P_{cor(\%)} = 22.03 - 0.01839 \cdot H_i + 0.0000094 \cdot H_i^2 \quad (2)$$

where,
$P_{cor(\%)}$ is the annual correction as a percentage of mean annual precipitation estimated of each grid point and
H_i is the elevation of these points.

On the basis of equation (2) the corrected annual precipitation was calculated for each grid point according to the formula

$$P_{cor,\ an} = P_{np}(1 + P_{cor(\%)}/100) \quad (3)$$

where,
$P_{cor,\ an}$ is the corrected mean annual precipitation,
P_{np} is the mean annual estimated precipitation at the grid point, and
$P_{cor(\%)}$ is the percentage of correction figured into annual precipitation.

According to Mendel and Golf (1990), the mean annual temperature can be used for characterising the evapotranspiration conditions on the territory of Slovakia. They found the relationship between mean annual temperature and altitude in Slovakia based on the study of data from 36 meteorological stations. The obtained formula took the inductive form

$$T_i = 10.1 - 0.0052 \cdot H_i \quad (4)$$

where,
T_i is the mean annual air temperature calculated for each grid point in the catchment and
H_i is its altitude.

From the estimated mean annual air temperature at each grid point we can calculate the mean potential evapotranspiration by the formula in Novak (1994, 1995):

$$PET_i = 210.0 + 50.0 \cdot T_i \quad (5)$$

where,
PET_i is the calculated mean annual potential evapotranspiration and
T_i the mean annual air temperature at each grid point.

The relationship between mean annual potential evapotranspiration and the mean annual air temperature was estimated with data from 48 meteorological stations of Slovakia. If we substitute equation (4) with equation (5), we can calculate the annual potential evapotranspiration as follows.

$$PET_i = 715.0 - 0.26 \cdot H_i \quad (6)$$

We see that the mean annual potential evapotranspiration can be directly calculated by equation (6), a relationship dependent on altitude only. Therefore we can calculate the mean annual potential evapotranspiration directly for each grid point. Using the Mezencev formula published by Babkin and Vuglinskij (1982) or the formula described by Novak (1994), we can estimate the mean annual actual evapotranspiration from the relationship

$$AET_i/PET_I = (1 + (P_i/PET_i)^{-n})^{-1/n} \quad (7)$$

where,
AET_i is the mean annual actual evapotranspiration,
P_i the mean annual measured or corrected precipitation, and
n is an exponent found by analysis of 51 meteorological stations of Slovakia.

By approximation of the graphical exponential function described by Novak (1994), the exponent, n, is found to be equal to 2.508. For a direct calculation of the mean annual actual evapotranspiration, equation (7) can be rewritten in the form

$$AET_i = PET_i.(1 + (P_i/PET_i)^{-5/2})^{-2/5} \quad (8)$$

If we calculate the mean annual actual evapotranspiration for each grid point in the study catchment by equation (8) (using the uncorrected or corrected precipitation), we obtain the point water balance components. The runoff water balance component is measured directly in the Svidnik cross-section. From all three water balance components we can estimate the water balance for a study catchment by the known water balance formula (1) in the form

$$R_1 = P - AET \quad (9)$$

$$R_2 = P_{cor,\,an} - AET \quad (10)$$

where,
R_1 is the mean annual runoff calculated by using the mean annual uncorrected precipitation and actual evapotranspiration and
R_2 the mean annual runoff calculated by using the corrected mean annual precipitation and actual evapotranspiration.

Results of the Mean Annual Water Balance Calculation

The calculation of the annual water balance components under the methodological approach described in this paper starts off with the measured precipitation of four rain gauge stations and an estimation of it for each grid point in the catchment grid system, as well as a mean estimation over the study catchment. The calculated mean annual precipitation for the period from 1965/66 to 1984/85 was 789.9mm. The mean annual correction in percentage calculated by equation (2) was 15.39 per cent and the corrected annual precipitation calculated by equation (3) was 911.46mm. The mean annual temperature estimated by equation (4) was 7.61°C. From equation (5) or (6) the mean annual potential evapotranspiration worked out to 590.72mm. Equation (8) for uncorrected annual precipitation and mean annual potential evapotranspiration (ratio 1.33) yielded a ratio of mean annual actual to mean annual potential evapotranspiration of 0.85, and hence an estimated mean annual actual evapotranspiration of 502.1mm. For corrected precipitation, the ratio of corrected and potential evapotranspiration is 1.55, so that the mean annual actual evapotranspiration was 525.7mm (under a ratio of actual to potential evapotranspiration of 0.89). The mean measured runoff at the Svidnik cross-section was 404.1mm. The calculated mean runoff by equation (9) was 287.8mm, and by equation (10), 386.4mm. The obtained results show that the differences between the calculated mean runoff from equation (9) and the measured runoff was 116.3mm (28.8%) and from equation (10), 17.7mm (4.4%). According to Molnar et al. (1990) the runoff is usually observed with an accuracy of up to five per cent, which is not achieved by any other components of the water balance. By using the water balance equation (1) with computed runoff components from equations (9 and 10), the sum of the three water balance components is equal to zero, whereas by using the measured runoff component (404.1mm) the water balance equation (1) yields a deviation of -116.3mm in combinatioin with the uncorrected mean annual precipitation, though only -18.3mm with the corrected precipitation. Accordingly we see that the correction of precipitation measurements is necessary when calculating the mean annual water balance in midland and highland mountainous catchments.

Conclusion

The presented methodological approach provides a way to calculate the mean annual water balance components indirectly by known measured precipitation in mountain catchments, by using grid point elevations of the sub-divided catchment. A comparison of the obtained results shows that the method presented is suitable for approximation of mean annual water balance components at various elevations in the mountainous catchments of Slovakia.

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