Method for correction of annual precipitation records using the water balance approach*

Yuri A. Salo

Northern Water Problems Institute, Karelian Research Centre, Russian Academy of Sciences, A. Nevskogo, 50, Petrozavodsk, Karelia, 185030 Russia. E-mail: *yuris@nwpi.krc.karelia.ru*

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Abstract Precipitation gauge measurements suffer from several sources of errors which can strongly influence their accuracy. The method proposed in the paper is based on the correction of annual precipitation records for a given river basin using the water balance equation. The main advantage of the approach is in using the annual runoff records and air temperature data, which are measured more accurately than the annual precipitation amount. Two versions of the computation scheme (for a multi-year period and for an annual interval) are presented and discussed. The water balance equation taken into account in this study combines the area averaged annual measured precipitation, runoff, evapotransporation and, over an annual time scale, the change in moisture in surface and undersurface storages. The Ol'decop formula for calculation of evapotranspiration together with the improved regional formula for potential evaporation as a function of annual air temperature is used in this study. It has been determined for the annual time interval that the storage of water in a basin is strongly dependent on annual air temperature and, to a lesser extent, on precipitation. An example of the method application for two catchments situated in Northwest Russia is presented, too.

Keywords Evapotranspiration; precipitation; precipitation correction; river basin; water balance equation

Introduction

The inhomogeneity in precipitation records arises from the natural heterogeneity and because of errors associated with gauge installations. The most significant sources of rain-gauge and snow-gauge measurement errors are: (a) errors due to gauge types and their changes, (b) station relocation, and, (c) near-environmental changes and urbanization influences. As noted by Golubev (2003), the world precipitation network combines at the present time about 150 000 gauges, with more than 50 different types used. The employment of each of these gauge types needs a special technique for the correction of measured precipitation. Furthermore, the practical use of new gauges necessitates the development of corresponding methods for recalculation of the precipitation data measured in the past by earlier gauge types. The different methods for correction of measured precipitation have been discussed and applied, in particular, by Golubev (1981), Heino (1994), Førland *et al.* (1996) and Michelson (2004).

The method considered in this paper builds upon a different approach. It is based on correction of the annual precipitation records not for a given gauge type, but for a given territory (for example, for a river basin) using the well-known water balance equation. The main advantage of this approach is in using the annual runoff records and air temperature data, which are measured more accurately than the annual precipitation amount.

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A first attempt to develop and apply the method for the territory of Karelia (Russia) at large (Salo 2003) has shown that it can be suitable for correction of precipitation data for different catchments for a multi-year period.

The aims of the present study are as follows: (a) to define the principle of the balance-based method for correction of annual precipitation records, (b) to propose a simple technique for its practical realization, and (c) to test the method developed for drainage basins located in the Kola Peninsula and Karelia.

Methods

For a given river basin for a certain period, the water balance equation combines precipitation (P), evapotranspiration (E), river runoff (R), and temporary storage of water in a basin (W), as follows:

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

where ε is the error term on closure and total error (including random and systematical ones) of the calculation of the water balance components included in Equation (1). All values in Equation (1) are in mm (10^{-3} m).

The storage W is the most problematic component of the water budget. In this study we define this term as a sum of changes in surface storage (lakes, reservoirs, wetlands, snow cover, etc.) and in subsurface storage of groundwater for a certain period.

While precipitation and runoff are directly measurable, evapotranspiration is most commonly estimated by more or less empirical equations. Usually, evapotranspiration is considered as a function $E(P,E_0)$, where E_0 is the potential rate of evaporation (Vershinin 1999). The latter value may be expressed as $E_0(T)$, where T is the mean air temperature for a given basin as a whole for the given period. In particular, empirical equations of this kind were obtained by Turc (1955) for the annual potential rate of evaporation as a function of the annual air temperature (Vershinin *et al.* 1981), and, more recently, by Postnikov (1999).

Hence, Equation (1) can be written in the resulting form as

$$P - R - E[P, E_0(T)] + W + \varepsilon = 0. \qquad (2)$$

The well-known formulae for estimation of evapotranspiration as a function of P and E_0 have been developed by Shreiber, Ol'decop, Turc, and Budyko. These methods have been described, in particular, by Vershinin *et al.* (1981), Arora (2002), and Brutsaert (1985).

Comparative analysis of these four formulae was carried out earlier (Salo 2003) and has shown the best performance of the Ol'decop formula for estimation of both annual and mean annual evapotranspiration for the river basins situated in Northwest Russia:

$$E = E_0 \tanh(P/E_0) \qquad (3)$$

where $\tanh(P/E_0)$ is the hyperbolic tangent function of the precipitation to potential evaporation ratio.

Parametrization of the relationship $E_0(T)$ carried out for 60 catchments with drainage areas ranging from 374 (River Olenitsa, Kola Peninsula) to 79 800 km^2 (River Volkhov) and with mean annual air temperatures ranging from -2.0 to 4.6 °C has shown that E_0 in Equation (1) can be represented as

$$E_0 = 329 + 62T + 2.14T^2 \qquad (4)$$

where T is the mean area averaged air temperature for a given basin, in °C.

It has been estimated that the standard error for the calculation of evapotranspiration using Equations (3) and (4) is about 5% of the evapotranspiration values, and 76% of errors are within ±40 mm.

Thus, the Ol'decop formula (3) has been improved by the addition of Equation (4), and can be considered as the regional empirical formula for the territory of Northwest Russia.

The formulae (3) and (4) were examined on an independent set of 45 catchments located over the territory of Finland using data on mean annual water balance and the map of annual air temperature norms published by Hyvärinen *et al.* (1995) and Heino (1994). The drainage areas of these catchments range from 325 km^2 to 22 515 km^2, and the lake percentages are within 0.2–30%. The evaluations have shown that the difference between the published values of evapotranspiration calculated by the standard technique and those computed from Equations (3) and (4) does not exceed 30% over the 45 basins tested. In 45% of cases the errors are within ±10%, and the difference within ±20% occurred in 80% of cases.

Equations (2)–(4) have formed the basis for the development of the method for the correction of both mean annual and annual precipitation records, as will be shown further.

Methods for the correction of precipitation records

Calculation scheme for the multi-year period

It is common knowledge in hydrology that for the long-time scale Equation (2) can be rewritten in an equilibrium form, as follows:

$$P - R - E[P, E_0(T)] = 0 \tag{5}$$

Using Equations (3)–(5), a simple calculation procedure of precipitation correction for the long-term period was developed (Salo 2003). A block diagram of the calculation algorithm is given in Figure 1, where all values are the mean annual area averaged ones, calculated for a given river basin by the usual techniques.

The step-by-step order of correction is the following.

At the first step the input variables are: initial (uncorrected) precipitation P, air temperature T, and river runoff from the basin R. In accordance with the plan (Figure 1), the values E_0 and E, and the residual ε of the water balance equation are calculated in turn, one after another. If $\varepsilon \neq 0$, the initial precipitation value must be increased by the value Δ. It is important that the sign of the value Δ is negative because the initial measured precipitations are lower than the "true" precipitations. At the second step the same calculations are repeated using values $(P - \Delta)$, T and R. At the next step and further the calculations are repeated analogously to the second step until $\Delta = 0$. Usually, two to four iterations is enough to reach $\Delta = 0$. When this condition is reached, the calculations are finished and at the output we have: (a) precipitation P_{CORR} obtained at the last step (and, consequently, corrected); (b)

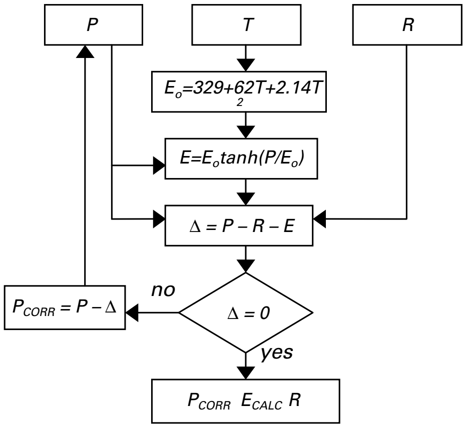

Figure 1 Block diagram of precipitation correction for the long-term period

evapotranspiration E_{CALC} calculated as a function of P_{CORR} and $E_0(T)$; and (c) river runoff R without changes. After the correction in accordance with the given plan, all water balance elements included in Equation (5) are in mutual conformity $P_{CORR} = R + E_{CALC}$, which is obvious for the long-term average values (or norms) of these elements.

Calculation scheme for the annual time interval

For a relatively short-time scale, like one calendar or water year, the storage of water in a basin (W) cannot be set equal to zero, and the water balance equation for the annual time interval can be written as

$$P - R - E[P, E_0(T)] + W + \varepsilon = 0. \tag{6}$$

It is assumed that the value ε in Equation (6) is no equal to zero but it is included in W. This assumption is partially based on the fact that there is considerable uncertainty in the water budget calculation associated with the accuracy of initial data.

It has been determined for several catchments located in the Kola Peninsula and Karelia (Table 1 and Figure 2) that the value W is dependent on the area averaged annual air temperature T and precipitation P (Salo 2003). The gauge density over these catchments is from 2700 to 5100 km^2 per one site.

The equation of multiple regression of the relationship has been formulated as follows:

$$W = b_0 + b_1 T + b_2 P \tag{7}$$

where b_0, b_1, and b_2 are the empirical coefficients calculated for the studied river basin using the least square method (LSM).

It was found that the magnitude of these coefficients differs widely over the catchments. Thus, coefficient b_1 varies from -0.59 (Shuja River) to -0.73 (Ponoj River), while coefficient b_2 for these catchments varies from -0.01 to 0.18.

As one can see from Table 1, the leading parameter defining the magnitude of W is the air temperature. The coefficients of linear correlation between W and annual precipitation are lower, from -0.03 to 0.13 for relatively small river basins, and only for the whole territory of Karelia is the coefficient of correlation equal to 0.44, explaining only about 20% of the variability in W. The coefficients of multiple regression $R(W,T,P)$ differ widely over the basins also, but their magnitudes are still enough to use Equation (7) for practical calculation. For individual parametrization of Equation (7) for the studied river basins the period since the 1950s can be recommended due to the improvement in the quality of precipitation measurements since that time (Golubev 2003).

The calculation algorithm for correction of annual precipitation was developed using Equation (6), with Equations (3), (4) and (7) taken into consideration, too. It is clear from the block diagram (Figure 3) that the procedure of correction is the same as the above-described procedure for the

Table 1 Correlation of the water storage (W) with annual air temperature (T) and annual precipitation (P) for some catchments

			Coefficient of correlation		
River, station	**Area (km^2)**	**Period (yr)**	$r(W,T)$	$r(W,P)$	$R(W,T,P)$
Ponoj at Kanevka	10 200	1955–1990	−0.72	0.13	0.75
Tchirko-Kem at Jushkozero	8220	1955–1987	−0.67	0.03	0.68
Vodla at Pudozh	13 000	1956–1999	−0.61	0.08	0.65
Shuja at Besovetc	10 100	1955–1999	−0.59	−0.03	0.59
Karelia at large	174 200	1955–1999	−0.73	0.44	0.90

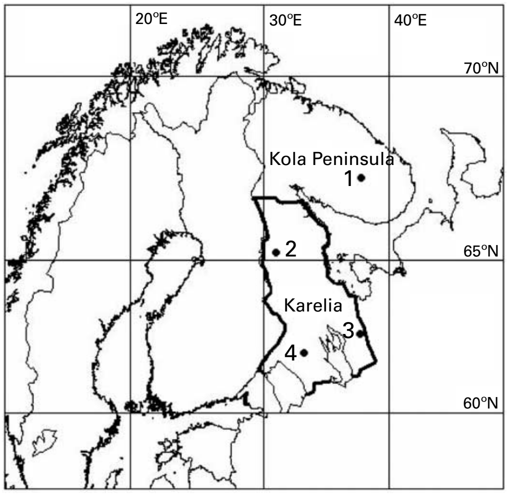

Figure 2 Location of catchments within the Kola Peninsula and Karelia. 1 – Ponoj River, 2 – Tchirko-Kem River, 3 – Vodla River, 4 – Shuja River

long-time period. The only addition is the block for $W(P,T)$ calculation. Consequently, the annual value of water storage in a basin (W_{CALC}) calculated by P_{CORR} and T is an output value, too.

An example of application of the method

Both calculation schemes were applied to two drainage areas situated in different physiographical settings.

The basin of the Ponoj River (Figure 2) is the largest catchment in the Kola Peninsula (forest–tundra zone), its drainage area at Kanevka settlement is 10 200 km^2, and annual area averaged air temperature over the period 1955–1990 varies from −3.7 to +1.2 °C, with a mean of −1.2 °C. The gauge density over the catchments is about 5100 km^2 per one site.

Records of annual runoff, as well as area averaged data on the annual precipitation and air temperature for the reference period, were used for employment of the calculation scheme for the short-term period (Figure 3). Multiple regression equation for W for this river basin was obtained using LSM, as follows:

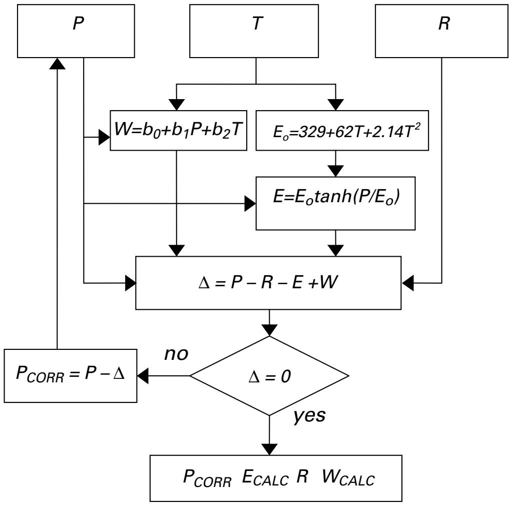

Figure 3 Block diagram of precipitation correction for the short-term period

$$W = 0.183P - 0.73T - 247. \qquad (8)$$

The coefficient of multiple regression $R(W,T,P)$ for the 36-year time series is equal to 0.75. After step-by-step correction in accordance with the diagram (Figure 3), the corrected time series of the annual precipitation were obtained.

As one can see from Figure 4, there is a marked difference between the corrected annual precipitation and the initial ones: on average over the 36-year period it has been equal to +89 mm, and a maximum difference of +188 mm was in 1960. In two years only – in 1966 and 1978 – the corrected annual values were lower than the measured ones, by 60 and 16 mm, respectively. These differences are insignificant because their proportion with reference to the corresponding annual precipitation is 16 and 3%, respectively. As follows from the calculation procedure, the main target of computations in accordance with the block diagram is not to simply increase the initial precipitation data, but to obtain the mutual conformity between all terms taken into consideration.

The mean annual precipitation over the 36-year period is $P = 449$ mm before, and $P_{\mathrm{CORR}} = 540$ mm after correction. Thus, the corrected norm of precipitation for the examined river basin exceeds the initial one by 20%. It has been calculated too that the mean annual evapotranspiration for the Ponoj River catchment is $E_{\mathrm{CALC}} = 248$ mm. Keeping in mind that the mean annual runoff for the given catchment is $R = 301$ mm, the error term of closure of the mean annual water balance was estimated. It equals 9 mm, or about 1.5% of P_{CORR}, that is, consequently, it corresponds quite well to the accuracy of the initial data. The results of the comparison of the mean annual precipitation and evapotranspiration values calculated above with those calculated using the computation scheme for a multi-year period ($P_{\mathrm{CORR}} = 552$ mm and $E_{\mathrm{CALC}} = 251$ mm, respectively) confirms their good agreement.

The calculation algorithm for the long-time conditions has been tested for the territory of the whole of Karelia with a drainage area of about 174 200 km^2. The 146-years' time series of the main water balance elements for the territory were obtained by Filatov *et al.* (2002), while a detailed description of these records is given in Salo (2003). The area averaged precipitation in that study was calculated by using the instrumental data on 28 meteorological stations; the gauge density is about 6200 km^2 per one site.

On this basis, three time series of the area averaged annual precipitation over the studied area for each of the 15-year moving sub-periods have been calculated and compared. Curve 1 in Figure 5 presents the initial precipitation records taken from directly climatologic yearbooks. Curve 2 is plotted after the initial month's precipitation data were corrected using correction coefficients taking into account the wind error (K_1), wetting loss (K_2), and recalculation coefficient for the change from the Wild type gauge (prior to 1955) to the Tretyakov gauge (K_3). Mean coefficients for the studied area were $K_1 = 1.25$, $K_2 = 1.11$,

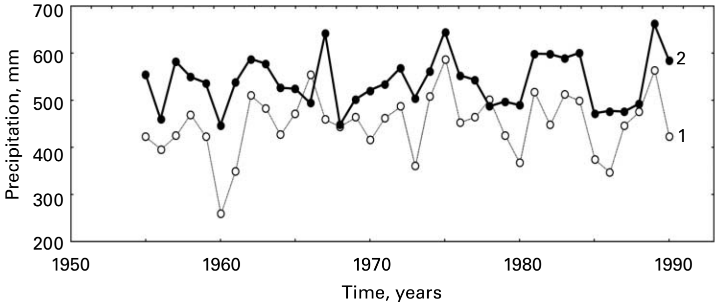

Figure 4 Measured (1) and corrected (2) annual precipitation for the Ponoj River at Kanevka for the period 1955–1990

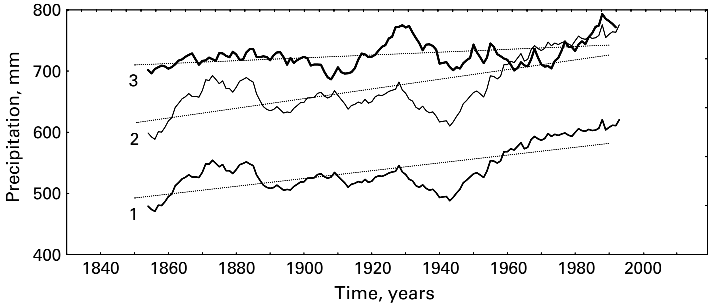

Figure 5 The 15-year moving average annual precipitation time series and its trend-lines for the whole Karelia for the period 1854–1999: 1 – initial published precipitation records, 2 – instrumental and formulae corrected ones, 3 – corrected using the proposed method

Table 2 Mean annual values (*M*, mm) and coefficients of linear trends (*k*, mm/100 yr) of water balance elements for the territory of Karelia for the period 1854–1999

	Published data		**Instrument and formulae corrected only**		**Corrected by proposed method**	
Water balance component	***M***	***k***	***M***	***k***	***M***	***k***
Precipitation, *P*	540	64	674	79	725	22
River runoff, *R*	321	−10	321	−10	321	−10
Evapotranspiration, *E*	368	38	397	40	406	32
Residual, $\Delta = P - R - E$	−149	36	−44	49	−2	0

and $K_3 = 1.05$ (Borisenkov *et al.* 1988). And, finally, based on the calculation scheme (Figure 1) the precipitation time series was obtained (curve 3 in Figure 5).

As can be seen in Figure 5, there are considerable differences in the obtained time series as well as in its linear trends. It can be seen also that the precipitation records corrected by both the standard and the proposed methods have been generally similar since the late 1950s, when the Tretyakov gauge (with a Tretyakov windshield) together with the standard correction techniques were included in the program of precipitation measurements over the Russian national observation network (Golubev 2003).

The results of calculations of the mean average water balance elements using the initial and the corrected precipitation data for a whole 146-year period are summarized in Table 2. As can be seen from the comparison of the water balance residuals, the best correspondence in both the mean average values and the coefficients of linear trend is in the case when the correction of precipitation using the calculation method is done.

Conclusions

This paper presents a newly developed balance-based technique for correction of annual precipitation records for annual and multi-year time scales. The main idea of this approach is based on a suggestion to correct the annual precipitation records for a given catchment using the area-averaged data on the annual precipitation, air temperature and annual runoff. These terms, together with the evapotransopiration term, are combined by the water balance equation. It has been pointed out earlier (Salo 2003), that the Ol'decop formula can be used for estimation of annual evapotranspiration for watersheds located over northwest Russia. In this case, the potential evaporation as a function of the annual air temperature can be calculated by using the regional empirical formula for the territory of Northwest Russia.

Two calculation schemes for correction of the initial precipitation have been considered in this paper. The first of them can be employed to correct the mean annual precipitation and to calculate the mean annual evaportanspiration for the multi-year period. The second one is intended for a short scale period in one water or calendar year. Additionally, the storage term was taken into consideration. In this study we define this term as a sum of changes in surface storage and in subsurface storage of groundwater for a certain period. It has been determined for the annual time interval that the storage of water in a basin is strongly dependent on annual air temperature and, to a lesser extent, on precipitation. It is important to note that the tested catchments are in the humid and relatively cold region. The norms of the annual precipitation and air temperature for the territory of the Kola Peninsula and Karelia are within 500–800 mm and from − 1.5 to 3.0 °C, respectively.

Further testing of the method developed as well as verification of Equations (3), (4) and (7) for different research basins will be required to be able to employ the method in practical hydrological and water balance computations. Application of the presented approach to different regions would certainly provide more insight into the ongoing problem.

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