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Using meteorological data for reconstruction of annual runoff series over an ungauged area: Empirical orthogonal function approach to Moldova–Southwest Ukraine region

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Abstract

The water-management transformation of runoff and the prospective change of global climate necessitate studying the climate forcing associated with runoff processes. This paper presents some quantitative estimations for the role of climatic factors in this process on an example of the Moldova–Southwest Ukraine region. Using empirical orthogonal functions, we establish the contribution of the annual evaporation, annual precipitation, and warm- and cold-season precipitation to the annual runoff for arid-zone rivers. An efficient approach for the reconstruction of natural annual runoff time series is developed and tested. The problems relating to (i) the estimation of annual runoff for rivers with lacking or deficient observational data, (ii) the definition of climate forcing for natural runoff parameters, and (iii) the modelling of annual runoff time series are solved.

Keywords: Climate forcing; Natural runoff; Empirical orthogonal function; Statistical structure

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1. Introduction

The Moldova–Southwest Ukraine region is characterized by short observational time series, and a water regime of rivers that is disturbed by the construction of artificial reservoirs for runoff control and by runoff transfer canals for irrigation. The map of annual runoff norms shows the “blank spot” due to deficient data (see Fig. 1c). To reconstruct the time series for the natural runoff (undisturbed by the economical activity), methods utilizing the relationship between runoff of studied rivers and rivers maintaining a natural water regime are usually used (Shiclomanov and Shiclomanov, 1998). However, zones of

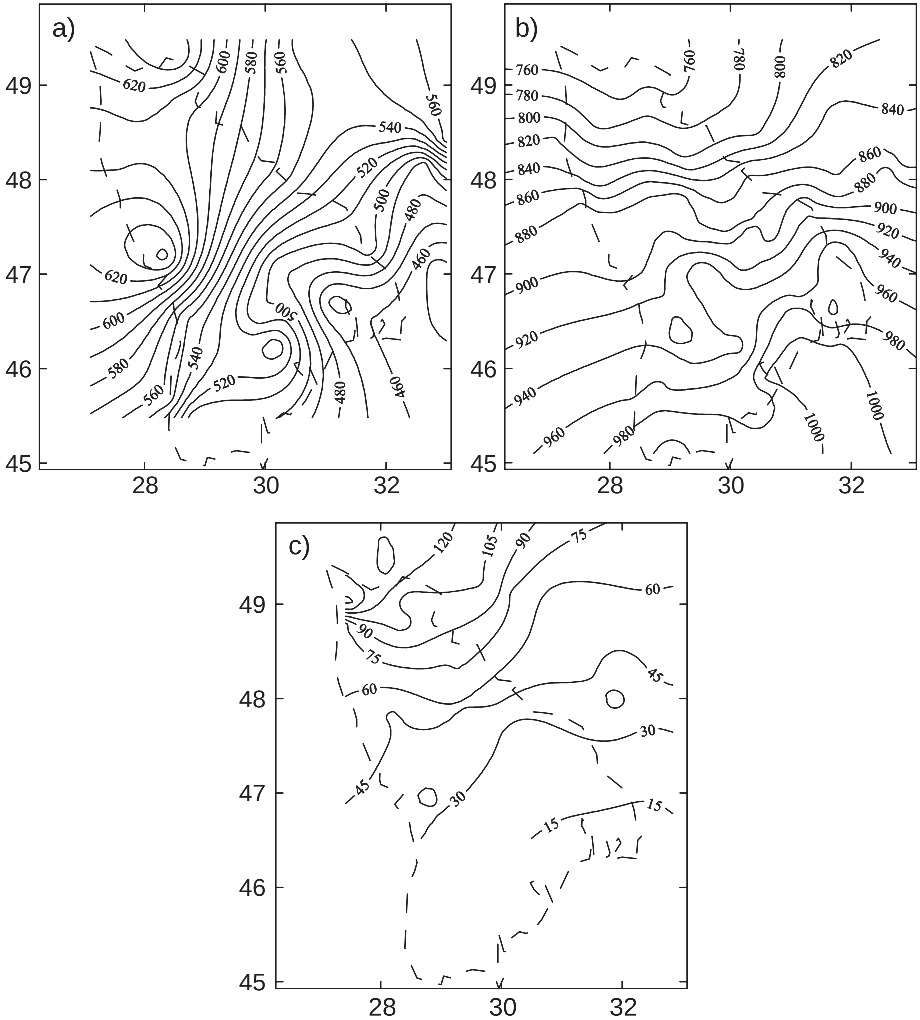

Fig. 1. The norms of (a) annual precipitation (mm), (b) potential evaporation (mm), and (c) annual runoff (mm) for the Moldova–Southwest Ukraine region. *X*-axis is the longitude (northern) and *Y*-axis is the latitude (eastern); the dashed curve indicates the boundary of the studied region.

natural runoff are presently practically absent within the boundaries of the studied region. Furthermore, runoff observations were started simultaneously with intensive water-management transformations in the catchments.

Natural runoff can be recovered by using water-management balance equations considering the inputs and outputs of domestic runoff for water-management needs. However the dataset on the water consumption for the studied region is also absent. Therefore the deficiency of runoff observations for both natural and economically disturbed conditions does not allow us to use conventional methods to reconstruct runoff. Nevertheless the studied region is characterized by a long and reliable meteorological data set. Thus, to reconstruct the annual runoff series it is reasonable to use meteorological data. It is well known that runoff forms as a result of the interaction of climatic factors depending on the ratio between the heat and moisture. Since the climatic factors obey the laws of zonality then the runoff spatial distribution obeys those laws and depicts more or less the climate forcing. The runoff dependence of the climatic factors is widely used in hydrological modelling (see, e.g. Gopchenko and Loboda, 1986; Loboda, 1998; Shun and Duffy, 1999; Uvo, 2003).

Parameterization of hydrometeorological fields by methods of mathematical analysis is widely used in modern hydrology (Stidd, 1967; Hisdal and Tveito, 1993; Kumar and Feofoula-Georgiou, 1993; Krasovskaia et al., 1999; Sauquet et al., 2000; Loboda and Glushkov, 2001; Pavlopoulus and Gupta, 2003). In this paper the contribution of climatic factors such as the annual evaporation, annual precipitation, and warm- and cold-season precipitation to the annual runoff in arid-zone rivers (Moldova–Southwest Ukraine) is determined. We show that the structures of fields for the first three eigenvectors of annual runoff are closely associated to that of meteorological fields whereas such relationship between the runoff and climatic factors is not found for other components of the expansion. It allows to assume that the first three components of the expansion can be used as a basis for runoff modelling. Such runoff represents only the climate forcing and, thus, is identical to the natural zonal runoff.

Thus the aim of present paper can be posed as the reconstruction of annual runoff time series for the arid-zone rivers of the Moldova–Southwest Ukraine by investigating the statistical structure of the spatial distribution for the climatic factors (precipitation and evaporation) using empirical orthogonal function analysis.

2. Area description, data and methodology

2.1. Studied region

The territory of the Moldova and Southwest Ukraine is characterized by considerable aridity. Annual precipitation (X) and potential evaporation (E_m) can be considered as quantitative characteristics for the resources of the moistening and heating correspondingly. The magnitude of potential evaporation is determined by the actinometric data with using the positive components of surface radiative budget (for details on the calculation procedure see Shuttleworth, 1991). Mean annual precipitation, $\bar{X}$, varies from 450 to 620 mm and southeastwardly decreases (Fig. 1a) whereas mean annual potential evaporation,

$\bar{E}_m$, varies from 780 to 1000 mm and southeastwardly increases (Fig. 1b). A comparative analysis of Fig. 1a and c shows that the spatial distribution of mean annual runoff, $\bar{Y}$, is defined by the mean annual precipitation. One can note that climate heating resources exceed significantly the moistening ones: the ratio for these two values, $\beta_X = \bar{X}/\bar{E}_m$, varies from 0.5 to 0.8. The runoff coefficient, $\eta = \bar{Y}/\bar{X}$, is close to 0.5.

Cyclonic activity associated with precipitation processes can be considered as one of the main factors forming the annual runoff. In winter months, the studied region is characterized by a high frequency of Mediterranean cyclones. Relatively warm and high-moistened air masses rise from the Mediterranean and Black Sea basins and move quasi-meridionally across the Ukraine. During the warm period (from March to November) anticyclonic rainless weather with high temperatures dominates over Southwest Ukraine. The cyclonic centres move mainly across Northern Europe and rainfall over Ukraine is caused by thermodynamic instability of the air masses. In spite of the fact that warm-season rainfall exceeds cold-season precipitation, the latter characterises the annual runoff. The cold-season precipitation is usually accumulated as a snow cover on watersheds. If temperature increases above 0 °C then the snow melts and the spring flood, which determines the main part of annual runoff for the arid-zone rivers, develops. On the other hand, except for the years with abnormal large water content, the warm-season precipitation is consumed almost entirely by evaporation from the surface.

2.2. Data

In this study we investigate the fields of annual runoff, annual precipitation, and warm- and cold-season precipitation over the studied region during 1951–1980. This 30-year period contains an equal number of high- and low-flow years that forms one cycle for the fluctuations of annual runoff and precipitation. In the studied region, the numbers of meteorological and hydrological sites are 27 and 26 respectively. First we generated the matrices of initial data with dimensions 30×27 and 30×26. Then we calculated the covariance matrix and correlation matrix that contain the information on statistical structures for the fields of runoff and precipitation. Finally, by using kriging techniques (Matheron, 1971), we interpolated the spatial characteristics into the studied territory, previously divided into 5×5 km squares.

2.3. Group analysis method

The runoff observation data are reliable when the time series have lengths of 50–100 years, but in most cases this length is far shorter. The situation is complicated by the variations of water regime due to water-management activities. These circumstances mean that many rivers are insufficiently studied. Nevertheless, the lack of data can partly be compensated by the spatial generalization of runoff characteristics.

To theoretically justify the above mentioned relationships, we use the group analysis method which considers the spatial variance of runoff as well as the components of this variance (Kritskiy and Menkel, 1982; Bolgov and Loboda, 1997). Here, we consider all hydrological or meteorological sites for the considered region as such a group. Using the spatial variance of statistical parameters, we establish the possibility of spatial averaging for the statistical parameters (e.g. mean values) of precipitation for intra-annual intervals.

The spatial variance, σ_S^2, of a given statistical parameter A is determined by

$$\sigma_S^2 = \frac{\sum_{j=1}^{k} (A_j - A_m)^2}{k-1}, \tag{1}$$

where k is the number of the statistical parameters combined into one group, A_j is the statistical parameter for j-th hydrometeorological site contained in chosen group, A_m is the mean value of the statistical parameter within the chosen group.

The spatial variance, σ_S^2, is considered as the sum of random, σ_r^2, and geographical, σ_g^2, components

$$\sigma_S^2 = \sigma_r^2 + \sigma_g^2. \tag{2}$$

The random component is determined as a mean variance for the selected statistical parameter within the group of objects

$$\sigma_r^2 = \frac{\sum_{j=1}^{k} \sigma_{A_j}^2}{k}, \tag{3}$$

where σ_{A_j} is the standard deviation for the statistical parameter A_j. Then the geographical component can be found from Eq. (2)

$$\sigma_g^2 = \sigma_S^2 - \sigma_r^2. \tag{4}$$

If the condition

$$\frac{\sigma_r^2}{\sigma_S^2} > \frac{\sigma_g^2}{\sigma_S^2} \tag{5}$$

is satisfied then one can conclude that the spatial distribution of the considered statistical parameter is mainly determined by random properties of joint time series. Hence the statistical parameters of the group can be justifiably averaged within the studied region.

2.4. Empirical orthogonal functions

The main idea of using empirical orthogonal functions (EOF) is to suggest a linear transformation of the original data, producing a new set of orthogonal functions, which simplifies and excludes redundant information. This method (exploiting the idea of singular value decomposition) is similar to those based on principal component analysis or eigenvector analysis. The theory and practice of expansion into the EOF has been considered, for example, by Holmström (1963), Obled and Creutin (1986), Rao and Hsieh (1991), Hisdal and Tveito (1993), Krasovskaia et al. (1999), Sauquet et al. (2000), and Uvo (2003). The expansion into EOF has the form

$$\varphi_{ij} = \sum_{k=1}^{m} U_{ki} z_{kj}, \tag{6}$$

where $i=1, \ldots, m$; $j=1, \ldots, n$; m is the number of sites; n is the series length; φ_{ij} are i-th the components of the j-th random vector for the centralized and normalized data; U_{ki} are the weight coefficients (basis functions) representing the contribution of the i-th site in the k-th component (in other words, U_{ki} are the components of the eigenvectors of the correlation matrix); z_{kj} are the time dependent functions of the k-th component of expansion (the so-called amplitude functions). It can be noted that the weight coefficients U_{ki} vary between the series but are constant in time.

The new set of functions φ_{ij} is empirical in the sense that these functions are based only on the original series themselves and are not restricted to any predetermined polynomial form. The set of EOF is usually arranged in descending order according to the proportion of variance explained by each function. An important property is that a small number of functions reproduce a large part of the total variance.

If the expansion in the eigenvector basis set is realized not from the correlation matrix, but from the covariance one, then the sum of variances of the principal components is equal to the summary variance for the original series. This representation explains more obviously the essence of the principal component method since these uncorrelated linear combinations of the original variables contain the variance included in the m variables of the original data. A few of the largest eigenvalues ($\lambda_1 > \lambda_2 > \ldots > \lambda_m$) embrace the main part of the total variance of the field and so, analyzing the results of the expansion, we concentrate on the first few characteristic values and components. Since large-scale atmospheric processes are characterized by large variance then it can be assumed that the first few components represent these processes.

If it is necessary to exclude the influence of uninformative physical processes for the generation of hydrometeorological fields, the first components only are used to perform the reverse transition from the components to the original series. This technique is called the procedure of "original data filtration". The filtered values of $\tilde{x}_{ij}$, the original variable, can be obtained using the following equation (Obled and Creutin, 1986)

$$\tilde{x}_{ij} = \bar{x}_i + \sigma_i \sum_{k=1}^{p} U_{ki} z_{ki} + \varepsilon, \tag{7}$$

$$\tilde{x}_{ij} = \bar{x}_i + \sum_{k=1}^{p} w_{ki} z_{ki} + \varepsilon, \tag{8}$$

where $\bar{x}_i$ and σ_i are the mean value and standard deviation of the original series; p is the number of principal components taken into account; ε is the approximation error due to the reduction of the number (from n) of principal components taken into account; $w_{ki}=(\sigma_i U_{ki})$ are the weight coefficients of the principal components, which are the elements of eigenvectors in the covariance matrix.

It should be noted that the EOF analysis is not a unique decomposition procedure to investigate the spatio-temporal behaviour of hydrometeorological fields. For example, Shun and Duffy (1999) used the multichannel Singular Spectrum Analysis. Among statistical techniques, linear methods are frequently used: simple or multivariate regression (Chen and Chen, 1999), CCA (Busuioc et al., 1999, 2001). Non-linear approaches, such as neural networks (Cavazos, 1999) and circulation classification (Goodess and Palutikof, 1998) have recently been developed.

3. Application to the Moldova–Southwest Ukraine region

3.1. Statistical characteristics for the warm- and cold-season precipitation

Our estimations for the considered territory show (see Eq. (5)) that the ratio of the geographical component of variance to the spatial one for the mean precipitation during the cold season tends to zero so that the ratio for the random component is close to 1. Thus we conclude that the spatial variance of mean cold-season precipitation is mainly (>90%) defined by the approximation error due to relatively short time series. Thus the mean cold-season precipitation within the studied region can be considered as a constant that equals approximately 110 mm. The time variability determined by the coefficient of variation, C_v, increases southwardly and varies from 0.37 in the north to 0.48 in the south. This variability cannot be averaged within the studied region. The mean ratio of the coefficient of skewness to the coefficient of variation, C_s/C_v, is equal to 2 whereas the coefficient of autocorrelation is equal to 0.1, i.e. a relationship between the warm-season precipitation for the preceding and following years is not observed.

As was mentioned above, the warm-season precipitation gives the main contribution to the annual precipitation. Therefore the relationship between the spatial distribution of these variables is significant. The norms of warm-season precipitation vary from 250 to 550 mm. The geographical component of variance for these norms is very large and cannot be averaged; on the contrary, the spatial variability of the coefficient of variation is not large and the mean value for this characteristic is equal to 0.29.

The meteorological fields are influenced by the various atmospheric processes with spatial scales from meso- to macro-. The climate forcing of annual runoff is not in doubt, so one can logically assume that same processes generate the field of annual runoff.

3.2. Forcing of annual runoff by warm- and cold-season precipitation

The first component of the EOF expansion of runoff time series represents the influence of the atmospheric processes with the largest (global) scale. This component contains 56% of the variance of the original time series of annual precipitation and 64% for the annual runoff. The analysis of the intra-annual precipitation shows that the contribution of the first component in the distribution of cold-season precipitation is most significant (77%) whereas for the case of warm-season precipitation the forcing by this component is less important (48%). This finding confirms that the statistical characteristics of cold-season precipitation, contrary to that of the warm-season, are conditioned by the large-scale processes and not by the surface-specified local character. The contribution of the first component to the fields of annual precipitation depends on the structure of warm-season precipitation. The weight coefficients U_{1X} (annual precipitation) and $U_{1X,\mathrm{W}}$ (warm-season precipitation) are linearly dependent with the coefficient of correlation equal to 0.71. Such behaviour is also observed for the statistical structure of annual precipitation and runoff; namely the spatial distribution for the weight coefficients of the first component for annual runoff, U_{1Y}, is mainly determined by the structure of annual precipitation and this relationship can be formulated by

$$U_{1Y} = 0.8773U_{1X} + 0.0355, \quad r = 0.72. \tag{9}$$

Since the annual precipitation conforms with that of the warm season, the same relationship is obtained for the weight coefficients of first component for the annual runoff and warm-season precipitation

$$U_{1Y} = 0.573U_{1X,\mathrm{W}} + 0.0834, \quad r = 0.79. \tag{10}$$

To investigate the behaviour of time variability of the annual runoff, we use the amplitude functions of the EOF expansion for the precipitation and annual runoff. These functions for the first component of annual runoff are linearly connected to those of annual precipitation with the averaged coefficient of correlation equal to 0.65. This finding confirms that time fluctuations of annual precipitation force the nature of runoff variations. By comparing the amplitude functions for the annual runoff and intra-annual precipitation we conclude that the cold-season precipitation plays a main part. The coefficient of correlation between the first amplitude functions for the annual runoff and cold-season precipitation is equal to 0.57 (see Fig. 2). The first amplitude function value of the annual runoff for 1980 deviates from the general behaviour due to the great warm season contribution. But this is not typical for the studied region. A relationship between the amplitude functions for the annual runoff and warm-season precipitation is not revealed.

3.3. Atmospheric processes and annual runoff

The region studied in this paper is located in a zone with insufficient moistening, where the surface evaporation influences the runoff. Again, using EOF analysis, we

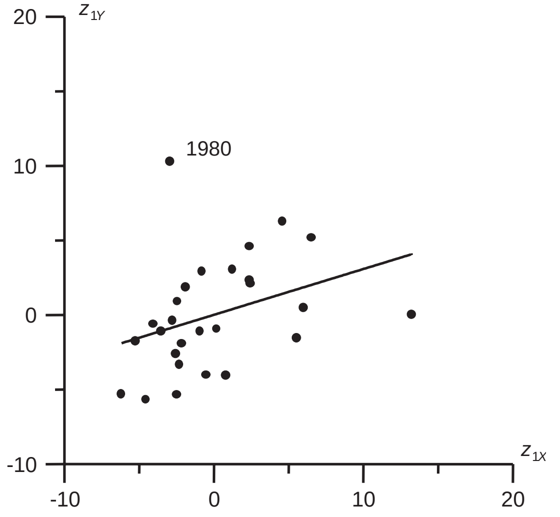

Fig. 2. The relationship between the first amplitude functions of the annual runoff and cold-season precipitation.

carried out the more complicated investigation for the fields of annual runoff, precipitation, and potential evaporation. Since the main part of the variance for the original series is described by the first three components, the investigation of the relationship between the weight coefficients for the annual runoff and above mentioned climatic factors seems to be well-formed. It is ascertained that the distribution of isolines for these weight coefficients is similar, which may be evidence of the same physical processes forming the annual runoff and climatic factors.

The first basis functions represent mostly the large-scale atmospheric processes and primarily the zonal circulation conditioned by these processes. The spatial structure of the latter is defined by the so-called teleconnection patterns in particular by the North Atlantic Oscillation (see, e.g. Glushkov et al., 2004). The seasonal location and activity of this process influence mainly the climatic background for the precipitation, temperature, and runoff over the European region as a whole and Ukraine in particular. Because we consider the large-scale process, its differential impact on individual sites within the studied region is not taken into account. The spatial distribution of first basis functions for the potential evaporation displays this situation especially well. Since the thermal background is more conservative than precipitation, the zonal circulation defines 93% of the spatio-temporal distribution for potential evaporation and 56–69% of that of precipitation and runoff.

The second basis functions (most probably) contain the information on the synoptic atmospheric processes. The dominance of westerlies in the nature of atmospheric processes over Ukraine defines the meridional distribution for the isolines of the weight coefficients of the second component in hydrometeorological fields. On the other hand, the pattern of the third basis functions shows that the annual runoff generated by mesoscale processes is the result of interaction between two climatic factors (precipitation and evaporation) the influences of which are in opposition.

Eqs. (7) and (8) can then be applied to simulate the runoff time series of insufficiently studied (or unstudied) rivers. For this purpose both the amplitude functions and the weight coefficients of first components after the EOF expansion are used. The long-term mean runoff $\bar{x}_i$ can be obtained from reliable sources for single regions. The advantage of such an approach consists in the dropping of uninformative fluctuations representing the individual properties of time series.

Preliminary analysis carried out for the fields of annual runoff shows that 69% of the total variance is explained by the first component of the EOF expansion, then successively 9%, 6%, 3%, and 2% by the next fourth largest components. Hence, by using the first three principal components representing more than 80% of the variance of the original series, the runoff for ungauged catchments with adequate accuracy can be reconstructed. For the studied region, the catchments for the interfluves of Danube–Dniestr and Dniestr–South Bug are characterized by null data (see Fig. 1c). To evaluate the weight coefficients we use the spatial behaviours determined from the part of the studied region which contains observational data. Recall that the amplitude functions are common for *all* catchments and can be also used for the runoff reconstruction of ungauged rivers. For example, to calculate the weight coefficients of the first component after the EOF expansion Eq. (10) can be applied. As it noted above, evaporation is the significant factor defining the annual runoff. Therefore, by using the results of the EOF expansion for the potential evaporation, we re-estimate Eq. (10) as

$$U_{1Y} = 0.9450U_{1X} - 1.95739U_{1E_m} + 0.3918, \quad r = 0.81, \tag{11}$$

where U_{1E_m} are the weight coefficients for the first component after the EOF expansion for the potential evaporation, and r is the coefficient of multiple linear regression.

3.4. Reconstruction of annual runoff using results of the EOF expansion

To describe the spatial distribution of weight coefficients of the EOF expansion, simpler relations can be used. As was mentioned above, the spatial distribution of the first three components can be associated with the climatic factors (annual precipitation, $\bar{X}$, and potential evaporation, $\bar{E}_m$) defining the annual runoff (Loboda, 2001). The first component of the EOF expansion, which is assigned with planetary-scale atmospheric processes, influences the climatic background of precipitation, potential evaporation, and runoff. The spatial distribution for the weight coefficients of this component for the annual runoff is very smooth over the studied region. Hence they can be considered as functions of spatial coordinates (x and y), and following linear trend equation display the relationship between these characteristics as follows:

$$w_1 = 0.0115y - 0.0051x - 0.0365, \quad r = 0.82. \tag{12}$$

The second component (Fig. 3) contains the information on synoptic scale processes. In absolute values, this component exerts a dominant influence. The weight coefficients of the second component for annual runoff (Fig. 3c) depends on the geographical longitude as follows

$$w_2 = 0.0172x - 0.5192, \quad r = 0.82. \tag{13}$$

In turn, the spatial distribution of the weight coefficients for the third component (not shown) of annual runoff depends on the geographical latitude as follows

$$w_3 = 0.0190y - 0.6670, \quad r = 0.73. \tag{14}$$

The long-term mean values for the climatic factors depend also on the spatial coordinates. From the above, we determined the relationship between the weight coefficients of expansion and the annual norms for the potential evaporation and precipitation as:

$$w_{1i} = -0.000884\bar{E}_m + 0.000361\bar{X} + 0.660, \quad r = 0.88, \tag{15}$$

$$w_{2i} = -0.0015\bar{E}_m - 0.0029\bar{X} + 3.014, \quad r = 0.73, \tag{16}$$

$$w_{3i} = 0.0018\bar{E}_m + 1.450, \quad r = -0.79. \tag{17}$$

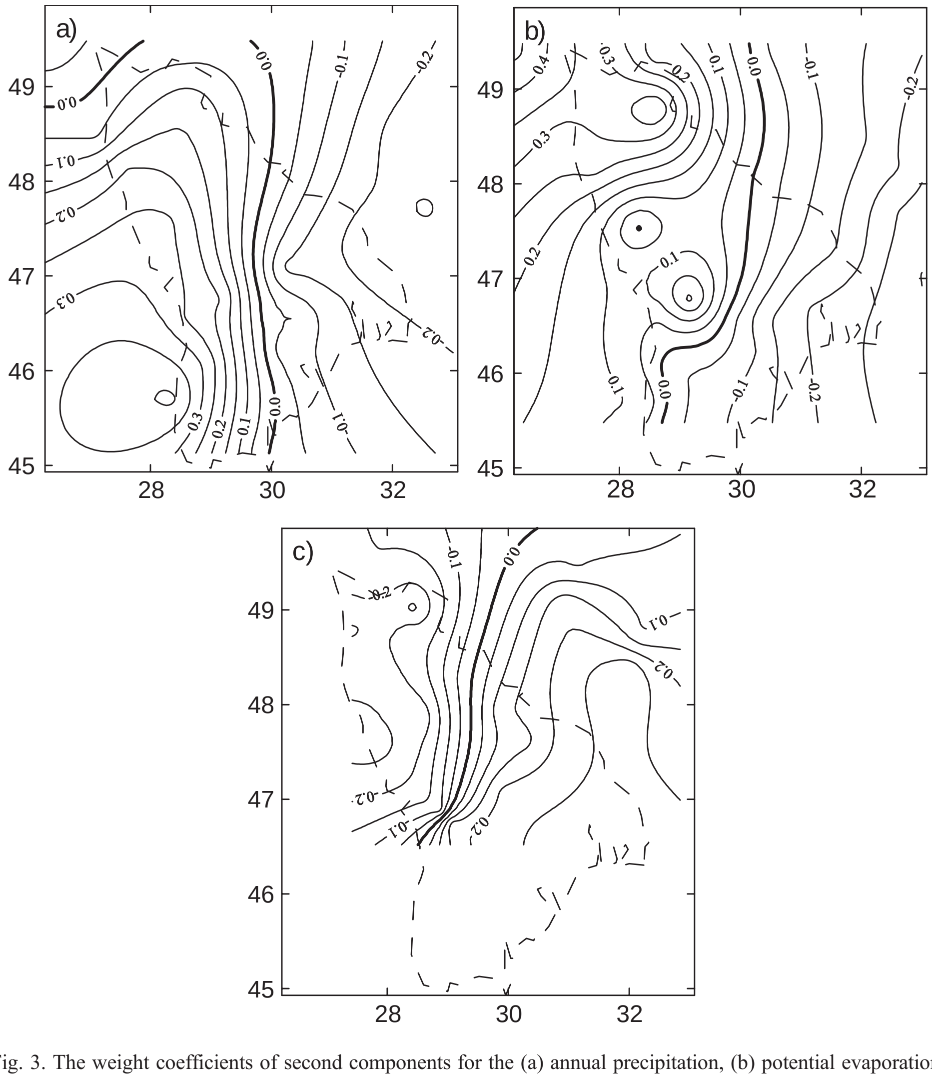

Fig. 3. The weight coefficients of second components for the (a) annual precipitation, (b) potential evaporation, and (c) annual runoff for the Moldova–Southwest Ukraine region. *X*-axis is the longitude (northern) and *Y*-axis is the latitude (eastern); the dashed curve indicates the boundary of the studied region.

The weight coefficients for the fourth component of the EOF expansion depend on the characteristics of the surface such as catchment mean height, H, and swampiness, f,

$$w_{4i} = -0.0025H - 0.0558f - 0.882, \quad r = 0.77. \tag{18}$$

The fifth component (not shown) is defined by the degree of water-management transformations; the largest values for this component correspond to the catchments with water regimes transformed appreciably due to runoff transfer by irrigation canals. Thus, if

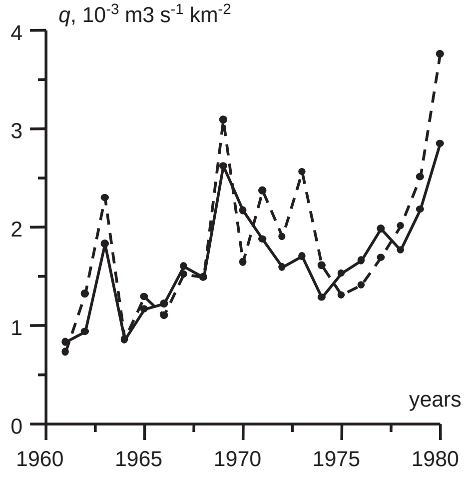

Fig. 4. The temporal variations of (a) reconstructed annual runoff (dashed line) and (b) observed annual runoff (solid line) for river Kogil'nic of the Moldova region.

only the first components of the EOF expansion are considered then the influence of both water-management transformations and other small-scale fluctuations are excluded.

The obtained results were used for the reconstruction of natural annual runoff. Input parameters are the norms of annual runoff, the amplitude functions obtained by the EOF expansion of annual runoff for whole region, and the weight functions for the first four components of expansion, which were calculated by means of Eqs. (12)–(18). As the criterion of accuracy we use the standard deviation (ε, presented by the percent from the actual value) for the calculated and actual values of annual natural runoff. By a series of numerical experiments we ascertained that the use of first three amplitude functions with the calculations by the Eqs. (8), (15), and (16) is optimal, the error amounts to $\pm$10% for neighbouring catchments where there are data of natural runoff. Fig. 4 shows the result of reconstruction of natural annual runoff set (dashed line) for one of the rivers (river Kogil'nic) in the studied region by using Eq. (8). The solid line gives observations (transformed by water-management activities). The error increases up to 15% due to water consumption for irrigation. For ungauged rivers, norms of natural annual runoff were defined from a map of isolines for the so-called climatic runoff that were calculated from meteorological data (Loboda, 1998; Gopchenko and Loboda, 2000).

4. Conclusion

By using the EOF analysis, the behaviour of the spatio-temporal distribution for the annual runoff in the Moldova–Southwest Ukraine region is considered as a result of climate forcing. The method used in this study allows evaluation of the contributions of different atmospheric processes to the formation of the annual runoff field. We show that the spatio-temporal behaviour of the annual runoff in the arid zone is defined by both precipitation and potential evaporation, and that the role of intra-annual precipitation is ascertained: the cold-season precipitation influences the temporal fluctuations whereas the warm-season precipitation impacts the spatial variability of annual runoff. We obtain the relations for the weight coefficients of first three components after the EOF expansion, which can be used to reconstruct the annual runoff of unstudied catchments in the Moldova–Southwest Ukraine region.

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