Assessing parameters of physically-based models for poorly gauged basins

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Abstract The possibility of using *a priori* information to reduce the amount of hydrological observation series data needed for the calibration of physically-based models of runoff generation has been studied. It is shown that by using measurements and runoff generation models in proxy-basins, the number of parameters requiring calibration can be limited to two toor three. Investigations were carried out using a physically-based model of runoff generation in the Kolyma and Seim river basins, Russia. The possibility of using observations from water-balance stations and experimental catchments as *a priori* data for assigning parameters of the models is demonstrated.

Key words ungauged basin; physically-based model; parameters; proxy-basin

INTRODUCTION

During the last few decades, runoff generation models have been shown to be effective as decision support tools for the planning and management of water resources systems, flood protection, watershed management, etc. However, application of these models depends, to a large extent, on the ability to assign their parameters, where there are insufficient runoff measurements for calibration of the model. Most river basins of the world, especially those of small and middle-sized rivers, are either ungauged or have short time series of runoff measurements. Therefore, when the experimental information is insufficient for estimation of the model parameters, it is important to supplement it with *a priori* information obtained from theoretical considerations, measurable catchment characteristics, laboratory experiments, and experimental observations in other catchments. The most obvious approaches for assigning *a priori* parameters are: to use their regionalized values, or values estimated for hydrologically similar catchments (proxy-basins); and the application of regionalized relationships between the parameters and measurable characteristics of the river basin. The capabilities of the first approach are limited, due to the great diversity of runoff generation mechanisms and the influence of catchment size on runoff generation. The capabilities of the second approach are broader and depend on runoff generation mechanisms predominant in the basin in question and on the model used.

The relationships between the parameters characterizing flood routing and basin characteristics have been used in hydrological practice for a long time. Much has been done to determine relationships, so-called pedotransfer functions, which allow the derivation of soil hydraulic characteristics from measured soil constants, and, thus, reduce the number of calibrated parameters in runoff models. In recent years, significant efforts have been made to obtain relationships between the parameters of conceptual models of runoff generation and measured catchment characteristics: for example, Uhlenbrook *et al*. (1999), Merz & Blöschl (2004), and the summary of the international MOPEX experiment presented by Chahinian *et al*., (2006). However, the results of these studies can hardly be considered encouraging. The cause of the restricted applicability of this approach is that the parameters of the conceptual models are too aggregated (i.e. physically complicated) and their values can vary over wide ranges, often taking on unrealistic values, thus affecting the reliability of the relationships obtained between the parameters and catchment characteristics.

The most suitable models for assimilation of *a priori* information are physically-based models of runoff generation. Most of the parameters of these models are, in principle, the measured catchment characteristics or physical constants, such as morphologic and hydraulic characteristics of catchments and channels, hydraulic and thermal properties of soil and snow, vegetation characteristics, etc. However, because the model is not a fully adequate representation of the described processes, is unable to reflect in fully the spatial variability of the catchment characteristics and meteorological inputs, or does not include some processes, etc., *a priori* information alone cannot, in most cases, ensure the necessary accuracy of runoff simulations. To achieve sufficient accuracy, some of the parameters of the physically-based runoff generation models should be adjusted through calibration against runoff measurements. As a result of the calibration, the parameters are replaced by their effective values; however, their physical sense is conserved and variations in the effective values lie within comparatively narrow limits. It can be expected that relationships between the effective parameters of the physically-based models and measured catchment characteristics will be tighter and more reliable than the respective relationships obtained for conceptual models, and it is possible to use shorter series of runoff measurements for calibration of the physically-based models.

In this paper, we present a procedure for estimating the parameters of physically-based models of runoff generation based on transfer of the parameters from proxy-basins. The procedure is aimed at the reducing the number of runoff observation series needed for calibration of the model.

CRITERIA OF HYDROLOGICAL SIMILARITY AND TRANSFER OF THE PARAMETERS FROM PROXY-BASINS

Hydrological similarity criteria depend on the choice of a physically-based model and, consequently, on the degree of the model sophistication. If we apply a sophisticated physically-based model, a large number of these criteria can exist and the possibility of finding similarity of the hydrological systems is substantially reduced. Therefore, in comparing hydrological systems, we can look at the similarity of individual processes alone, or at conditional similarity restricted by the closeness of some of the main similarity criteria selected depending on the most important processes in the problem under consideration.

In considering the similarity of runoff generation processes in river catchments, it is often convenient to determine similarity criteria separately for vertical water movement (infiltration and evaporation) at a point, horizontal flow through the catchment and river channel system, and spatial variability of catchment characteristics.

Strict enough similarity criteria for vertical water movement can be obtained by applying similarity theory to the equation of soil moisture diffusion. If we introduce characteristic scales of time (T_0), soil depth (H_0), soil porosity (θ_m), diffusion coefficient (D_0), and saturated hydraulic conductivity (K_s), we obtain the following similarity criteria for vertical moisture transfer (Kuchment & Gelfan, 2005):

$$\frac{K_s H_0}{D_0} = idem \tag{1}$$

$$\frac{K_s T_0}{\theta_m H_0} = idem \tag{2}$$

The first criterion is the Peclet number, that is the ratio of the rates of moisture transfer by gravitational filtration and capillary diffusion. The second criterion characterizes free soil capacity.

To estimate similarity in the water balance components, the following criteria can be used (e.g. Kuchment & Gelfan, 2005; Wagener *et al.*, 2007): (a) the gravitational filtration efficiency that is the ratio of the saturated hydraulic conductivity, K_s, to the mean precipitation rate R; (b) the capillary filtration efficiency that is the ratio of the mean rate of capillary filtration to the mean precipitation rate $D_0/(H_0R)$; (c) the aridity index that is the ratio of the mean annual potential evaporation E_p to the mean annual precipitation P; (d) the ratio of the transpiration E_{tr} to the soil evaporation E_s; (e) the shallow groundwater index that is the ratio of the mean rates of capillary to the hydraulic filtration; and (f) the coefficients of surface and groundwater flow.

From the experience gained in constructing physically-based models of runoff generation for many catchments, we developed the following procedure of transfer of the model parameters from hydrologically similar basins:

1. Using the similarity criteria, we select a relatively small proxy-basin for which sufficiently long observation series of runoff and other components of heat and water balances are available. In selection of the proxy-basin, an important role can be played by data accumulated at the water balance stations or experimental basins, where many basin characteristics are measured and special observations of water-balance components are carried out.
2. Measurements of parameters in the selected proxy-basin or parameter values obtained from their relations to catchment characteristics are used as the initial parameter values. A part of the parameters are adjusted through calibration. Sensitivity of calculated runoff hydrographs to the variation of all parameters is analysed. The parameters are ranked in significance, and this ranking is assumed to be the same for the main basin and for a proxy-basin (it may be part of the main basin).
3. *A priori* values of the parameters of the model constructed for the main basin are assigned using the results obtained for the proxy-basin and taking into account the ratio of sizes of the proxy-basin and the main basin. A few most important parameters of the model constructed for the main basin are refined by calibration against available runoff observations for a short period.

In the next sections, we demonstrate the applicability of the described procedure for assessing parameters of the models of runoff generation in the Kolyma and Seim basins, Russia. The basins are located in quite different physiographic conditions: the Kolyma basin is located in the continuous permafrost region covered by tundra and taiga in eastern Siberia, and the Seim basin is situated in the forested-steppe zone of European Russia.

ASSESSING PARAMETERS OF THE RUNOFF GENERATION MODEL IN THE KOLYMA BASIN

The physically-based model of runoff generation in the Upper Kolyma basin (the catchment area up to Ust-Srednikan is 99 400 km^2) is described in Kuchment *et al.* (2000). The model is based on a finite-element schematization of the catchment area and describes snow cover formation and snowmelt, thawing of the ground, evaporation, basin water storage dynamics, overland, subsurface and channel flow.

The developed model contains 12 parameters: volumetric soil porosity (θ_m); specific heat capacity of soil matrix (C_g); basin storage capacity (P_0); the coefficient k_E of the formula for evaporation rate; coefficient β of the relationship between the degree-day factor and snow density; coefficients a and b for determining thermal conductivity of unfrozen soil; Manning's roughness coefficients n_s for slope surface and n_r for river channels; the field capacity of soil (θ_f); the horizontal hydraulic conductivity near the soil surface (K_0); and the decay of horizontal hydraulic conductivity with depth of the active layer (φ).

As the proxy-basin, we used the 21 km^2-basin of the Kontaktovyi Creek located at the Kolyma River head and within the area of the Kolyma water balance station (KWBS). Based on the climatic characteristics and hydraulic soil characteristics taken from the literature and measurements, the following values of the hydrological similarity criteria presented in the previous section were obtained for the Kolyma and Kontaktovyi basins, respectively: the Peclet numbers (equation (1)) are 1.80 and 1.56, the free soil capacities (equation (2)) are 2.50 and 2.32; the gravitational filtration efficiencies are 221.4 and 192.3, and the capillary filtration efficiencies are 142.0 and 107.0.

To scale the statistical parameters of spatial snow distributions, the hypothesis of statistical self-similarity of snow cover presented and tested by Kuchment & Gelfan (2001) was applied. According to this hypothesis, the probability distribution characteristic of snow, S (e.g. snow water equivalent, snow depth) within any cell A_k of an area A is the same as the distribution over the whole area A if a scaling transformation of this variable within A_k is made. Such a scaling transformation is when the variable S is multiplied by a factor r^H, where r is a constant depending on the ratio of A_k to A, and H is the constant depending on a measure of spatial correlation of S. The condition of the equality of probability distributions of S within the area A_k of the proxy-basin and the area A of the main basin is presented as the following relationship between corresponding statistical moments $E\left[S_k^n\right]$ and $E\left[S_A^n\right]$ of order n:

$$E\left[S_k^n\right] = r^{nH} E\left[S_A^n\right] \tag{3}$$

where $E[\ ]$ is the expectation.

The procedure of model parameter assessment for the Kontaktovyi basin is described in detail by Gelfan (2005) and mentioned only briefly here.

The initial estimation of the parameters of the model of runoff generation in the Kontaktovyi basin was performed as follows. Three parameters (θ_m, a and b) were estimated from the available soil measurements at the KWBS. Specific heat capacity (C_g) was taken from literature data.

Free storage capacity P_0 at the beginning of the melt season and the coefficient k_E were determined by the empirical relationships obtained by Kuchment *et al*. (2000) on the basis of measurements done at the KWBS over 20 years (1965–1984). The coefficient β was adjusted by calibration against snow measurements for the same period. The remaining five parameters (θ_f, K_0, n_s, n_r and φ) were adjusted using observed discharge values at the Kontaktny Creek for 1967–1976. The calculated runoff hydrographs of Kontaktovyi Creek were found to be most sensitive to the parameters θ_f, k_E and P_0.

A priori values of the parameters of the runoff generation model for the Kolyma River basin were specified as follows. Nine parameters (P_0, θ_m, C_g, β, a, b, K_0, φ and n_s) were determined using either measured values or those assessed for the model of the proxy-basin. Three key-parameters (θ_f, k_E and n_r) were refined by calibration against measured discharges at the Kolyma River basin outlet. Values of these parameters estimated for the proxy-basin were considered as the initial values for calibration, and a search for the final values was conducted around these initial values. Calibration of the Kolyma basin model was carried out against the runoff observations. The efficiency criterion E of Nash & Sutcliffe (1970) was adopted to summarize the goodness-of-fit of the calculated and observed hydrographs. Between one and five years were used for calibration (1967, 1967–1968, …, 1967–1971), and five corresponding sets of the parameters were obtained. Each of the five parameter sets was used to validate the model against the observed hydrographs that were not used for calibration. Five evaluation periods corresponding to these five sets of the parameters include between five and nine years: 1968–1976, 1969–1976, …, 1972–1976, respectively. The efficiency criteria E obtained for five evaluation periods were compared with each other, as well as with the criterion E found from hydrograph calculations for 10 years (1967–1976) with the *a priori* values of all 12 parameters assessed for the proxy-basin. The model evaluation results obtained with differently assigned sets of the parameters are given in Fig. 1(a).

As one can see from Fig. 1(a), the use of nine parameters transferred from the proxy-basin and three key-parameters calibrated against two years of runoff observations in the main basin, enabled us to obtain significant improvement of the evaluation period results in comparison with those obtained without calibration (using *a priori* information alone). Beginning from two seasons, the extension of the calibration period does not result in visible improvement of the evaluation results. As an example, Fig. 2 shows comparison of the observed runoff hydrographs of the Kolyma River with the hydrographs calculated by the model calibrated using 2 and 5 years of observations.

ASSIGNING PARAMETERS OF THE RUNOFF GENERATION MODEL IN THE SEIM BASIN

The distributed physically-based model of runoff generation in the Seim basin (the catchment area up to the Ryshkovo is 7460 km^2) was presented by Kuchment & Gelfan (2002) and describes

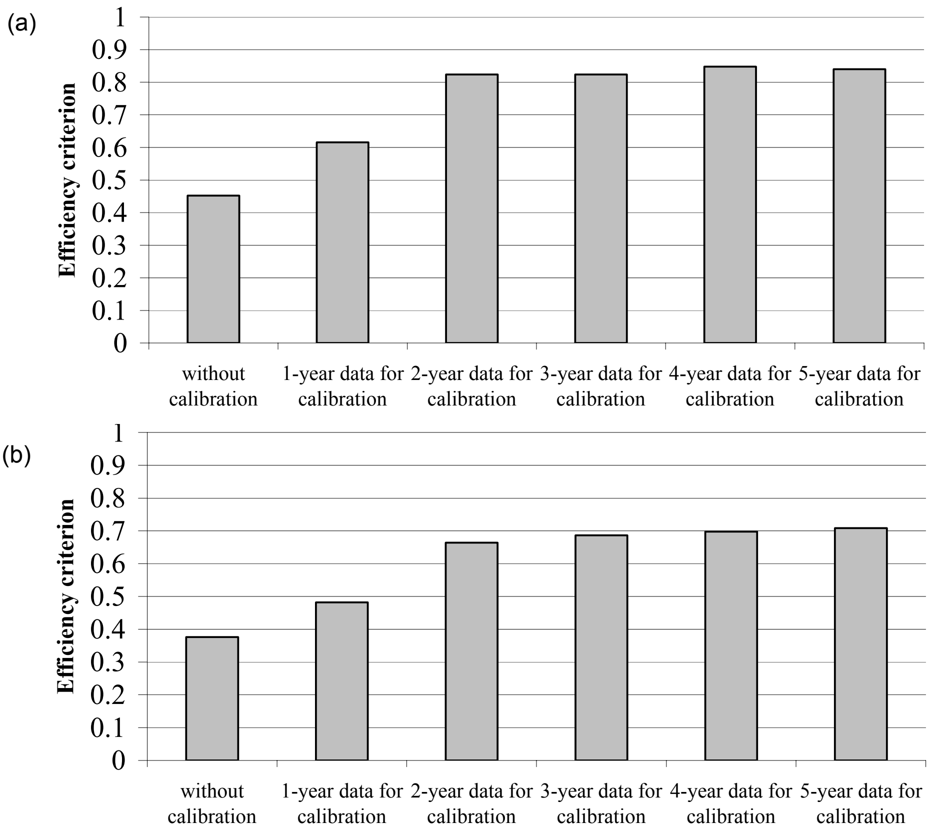

Fig. 1 Results of model validation obtained with differently assigned sets of the parameters: (a) Kolyma River and (b) Seim River.

processes of snow accumulation and melt, soil freezing and thawing, infiltration into frozen and unfrozen soil, evaporation, and overland and channel flow.

The model contains 14 parameters: six soil constants (the saturated hydraulic conductivity, K_s, the maximum hygroscopicity, θ_r; the wilting point, θ_w; the bulk density, ρ_b; the porosity, θ_m; and the field capacity, θ_f); the area-mean storage, P_0*, of the land surface depressions; the parameter of the formula for calculating soil moisture evaporation, k_E*; as well as n_s, n_r, C_g, β, a and b (for the last six parameters, designations are the same as in the previous section).

The 22-km^2 Yasenok Creek basin located within the Nizhnedevitskaya water balance station (NWBS) area, 80 km east of the Seim catchment, was chosen as the proxy-basin. For the Seim and Yasenok catchments, the following values of the hydrological similarity criteria were obtained, respectively: Peclet numbers 0.49 and 0.38; free soil capacity criteria 1.91 and 1.78; gravitational filtration efficiencies 83.7 and 66.7; and capillary filtration efficiencies 266.3 and 215.1. Comparing these values with the corresponding values obtained for the catchments of the Kolyma basin, one can conclude that the differences between similarity criteria for the catchments located in similar physiographic conditions are much smaller than those of catchments from different physiographic conditions. It should also be noted that, for the catchments in question, the gravitational filtration efficiency is lower and the capillary filtration efficiency is higher than those in the catchments of the Kolyma basin, which mainly has soils of a coarser texture.

The parameters of the runoff generation model for the Yasenok Creek were initially estimated as follows. The soil constants (except K_s) were assigned from the available measurements. The specific heat capacity of soil was obtained from the literature. The parameters a and b were calculated from their dependences on soil density. The parameter k_E* was estimated from the measurements of evaporation rates at the NWBS. The coefficient β was adjusted by calibration against the available snow measurements at the NWBS for 5 years (1969–1974). The remaining

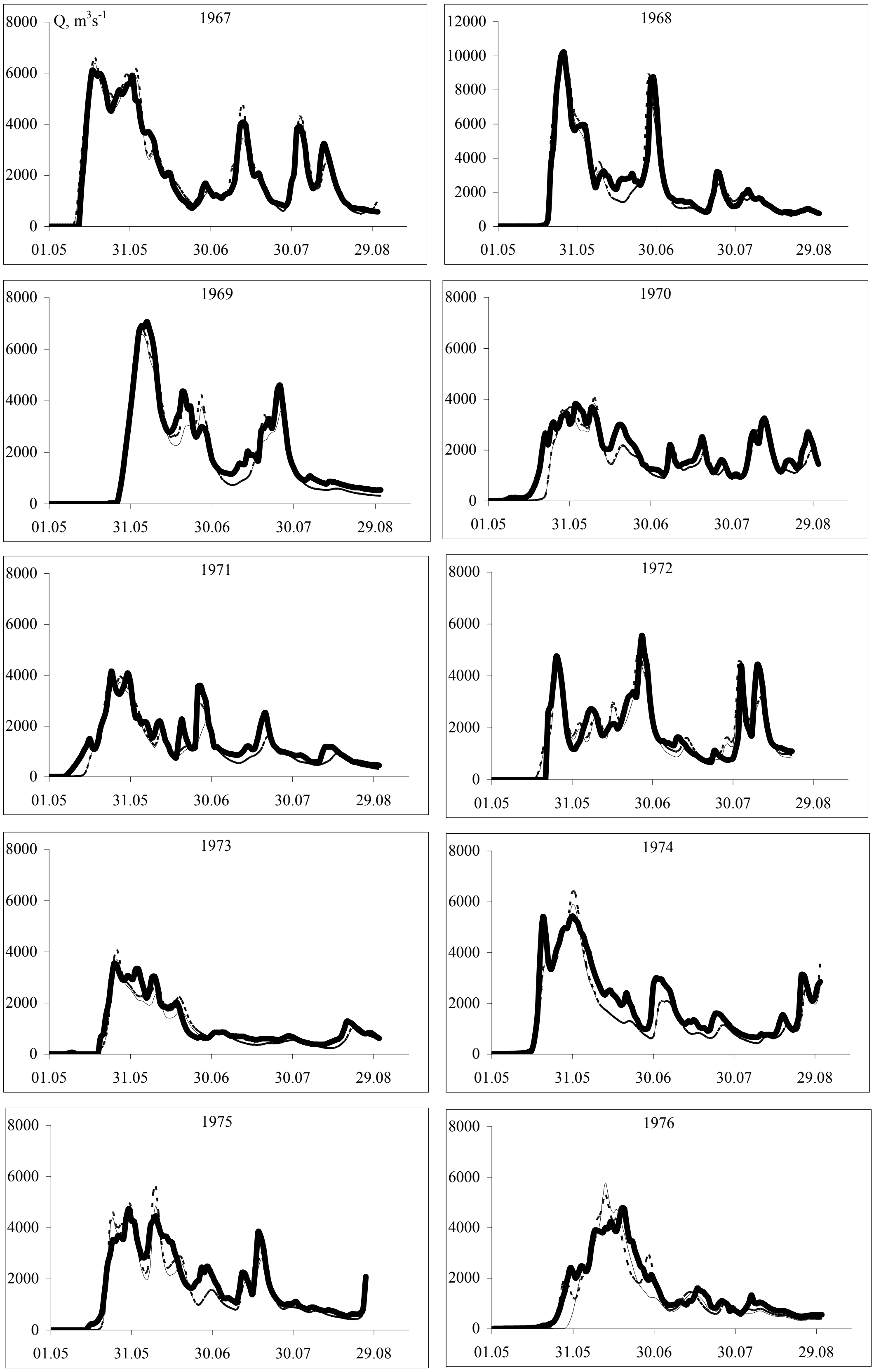

Fig. 2 Comparison of the hydrographs observed (bold line) with the hydrographs calculated by the model calibrated using the two (thin line) and five (dashed line) years of observations (Kolyma River).

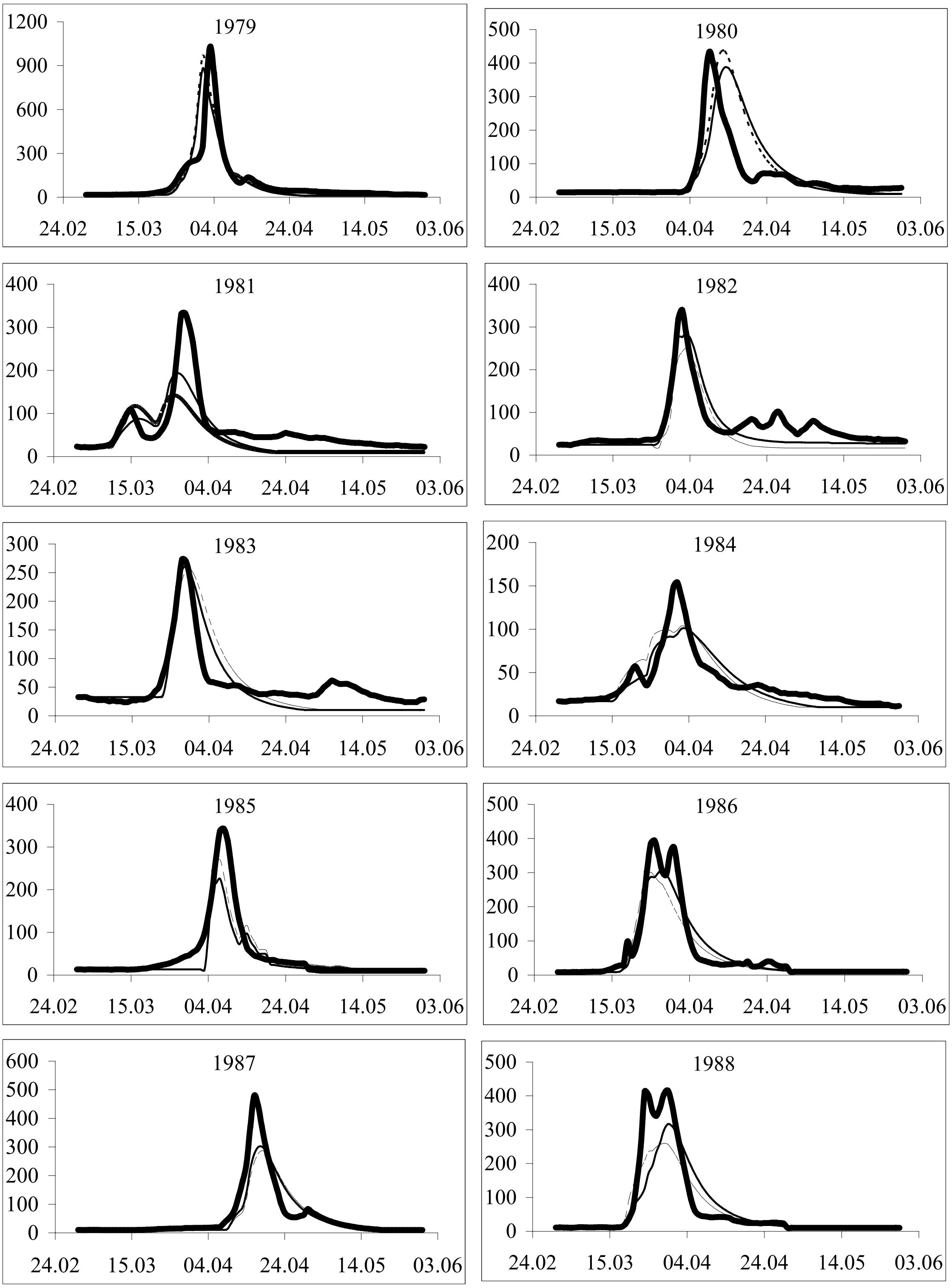

Fig. 3 Comparison of the hydrographs observed (bold line) with the hydrographs calculated by the model calibrated using the two (thin line) and five (dashed line) years of observations (Seim River).

four parameters (K_s, P_0*, n_s and n_r) were adjusted through calibration against observed discharge in the Yasenok Creek for the same years.

Sensitivity analysis was carried out and the calculated snowmelt runoff hydrographs was found to be most sensitive to the variation of K_s, β and n_r. As a result of the sensitivity analysis, the parameters of the Seim basin runoff generation model were finally assigned as follows. The soil constants of those soil types in the Seim catchment that were not involved in the NWBS measurements were specified from measurements at the agrometeorological stations located within this catchment. For the remaining parameters (except for the key parameters K_s, β and n_r), their *a priori* values obtained for the Yasenok basin model were taken. For scaling the parameters of spatial statistical distribution of saturated hydraulic conductivity, K_s, the hypothesis of statistical self-similarity of the logarithms of K_s was applied.

The key-parameters (K_s, β and n_r) were adjusted through calibration against observed hydrographs at the Seim River using the same procedure as applied for the Kolyma basin model. Between one and five years (1979, 1979–1980, …, 1979–1983) were used for calibration. The corresponding evaluation periods are between nine and five years: 1980–1988, 1981–1988, …, 1984–1988, respectively. The efficiency criteria *E* obtained for five evaluation periods were compared with each other as well as with the criterion *E* found from hydrograph calculations for 10 years (1979–1988) using the *a priori* values of all 14 parameters assessed for the proxy-basin. The model evaluation results obtained with differently assigned parameters are given in Fig. 1(b). Figure 3 shows the comparison of the observed runoff hydrographs of the Seim River with the hydrographs calculated by the model calibrated using two and five years of observations.

By comparing the results obtained for the Kolyma and Seim rivers, it may be seen that the extension of the calibration period from two to five years for the Seim model, as well as for the Kolyma model, resulted in no significant improvement. For both models, the calibration against short series produced better results than that with *a priori* information alone.

CONCLUSIONS

Physically-based models of runoff generation allow the assimilation of *a priori* information which can compensate, to a certain extent, for insufficiency of runoff measurements in poorly gauged basins. However, due to inadequacy of the model in terms of the described processes, spatial heterogeneity of catchment characteristics, data errors, etc., some of the model parameters must be adjusted through calibration against runoff data to ensure sufficient accuracy of runoff prediction. The data obtained from experimental measurements and modelling of runoff in proxy-basins give the opportunity to find *a priori* values of most parameters, resulting in substantial reduction of the length of runoff measurement series needed for calibration. The data from the water-balance stations and experimental river basins can be of great importance in choosing the proxy-basins.

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