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Assessment of extreme flood characteristics based on a dynamic-stochastic model of runoff generation and the probable maximum discharge

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Abstract A dynamic-stochastic model of flood generation consisting of a distributed physically-based model of snowmelt runoff genesis and a stochastic weather generator has been used for the assessment of extreme flood risk. Coupling this model with the Monte Carlo simulations of meteorological series allows the calculation of long series of runoff hydrographs and the exceedance probabilities of flood characteristics, as well as avoiding the application of the hypothesis of stationarity of hydrological series. However, for very rare events, the uncertainty in estimating flood risk because of the model inadequacy and insufficient lengths of the used data series may significantly increase. To decrease this uncertainty, it has been suggested that the peak discharge series obtained by dynamic-stochastic simulations be combined with the probable maximum discharge (PMD) calculated through the physically-based model of snowmelt runoff generation. This combining is achieved by fitting the estimated exceedance probabilities of simulated peak discharges by the Johnson distribution with the PMD as the parameter. Sensitivity of the fitted Johnson distribution to the errors of the PMD estimations is analysed. A case study was carried out for the Vyatka River basin in Russia (catchment area of 124 000 km^2) and the Seim River basin (catchment area of 7460 km^2).

Key words distributed hydrological model; flood risk; stochastic weather generator; probable maximum discharge

INTRODUCTION

In present-day hydrological practice, there are two main approaches to estimate extreme flood characteristics. The first is the traditional flood frequency analysis based on statistical treatment of the available records of flood peak discharges. The fundamental weakness of this approach to estimating floods of a large return period is widely-known (e.g. Singh & Strupczewsky, 2002), and it arises from the fact that the recorded data of flood extremes are usually too scarce and statistically non-homogeneous. The second approach is based on an assumption that there are some physical limits of rainfall or snowmelt rate for each region and for each season, and these values can be utilized for calculation of the hydrograph of the Probable Maximum Flood (PMF). In this approach, the probability of the desired possible maximum discharge is not estimated, which creates difficulties for decision makers with assessment of available uncertainty. Both aforementioned approaches are based on an implicit hypothesis of stationarity of hydrological series. However, the extreme flood characteristics can be significantly affected by human activity and climate change, and physical mechanisms of the extreme flood generation can differ significantly from ones of ordinary floods, so the stationarity hypothesis can lead to large errors in extreme flood assessment. Coupling the physically-based models of runoff generation (providing simulation of flood generation for a wide range of possible combinations of meteorological and hydrological conditions) with stochastic models of meteorological time series overcomes, to a significant extent, the shortcomings of both aforementioned approaches. The dynamic-stochastic models based on coupling stochastic models of meteorological inputs and deterministic runoff generation model have been developed, beginning with the pioneering work of Eagleson (1972), by many authors (Hebson & Wood, 1982; Diaz-Granados *et al.*, 1984; Kuchment & Gelfan, 1991; Franchini *et al.*, 1996; Blazkova & Beven, 1997; Blöschl & Sivapalan, 1997; Hashemi *et al.*, 2000; Kuchment & Gelfan, 2002; Haberlandt *et al.* 2008; Gelfan, 2010).

Kuchment & Gelfan (2002) coupled the Monte Carlo procedure of simulation of stochastic meteorological series (weather generators) with a detailed physically-based model of runoff generation that permits one to account for changes in drainage basin characteristics, the physical mechanisms of extreme floods and climate. The case study was carried out for snowmelt floods in the Seim River basin (7460 km^2 catchment area) where the majority of the land is ploughed, and forest occupies about 10% of the area. This study has shown that the dynamic-stochastic methodology can ensure a more reliable determination of the peak discharges of low exceedance probabilities than the usual statistical analysis when the meteorological series are substantially longer than the peak discharge series. However, because of the model inadequacy and insufficient lengths of the hydrometeorological series used, uncertainty in estimating peak discharges can quickly increase with decreasing exceedance probability for rare events.

In this paper, we develop the dynamic-stochastic methodology of estimation of the exceedance probabilities of snowmelt flood peak discharges using data for the mainly forested Vyatka River, and suggest a new methodology of the uncertainty reduction based on combining the peak discharge series obtained by dynamic-stochastic simulations with the probable maximum discharge (PMD) calculated through the physically-based model of snowmelt runoff generation. Because of the differences in runoff generation processes in the Vyatka River and the Seim River basins, there are distinctions in the physically-based models of snowmelt runoff generation for these basins, but the structure of stochastic weather generators for the Vyatka River and for the Seim River basins is the same.

DYNAMIC-STOCHASTIC MODEL OF RUNOFF GENERATION IN THE VYATKA RIVER BASIN

The Vyatka River starts in the foothills of the central Urals and continues into the East European Plain. The study area has flat terrain and mixed vegetation cover. In its northern, part more than 80% of the area is covered by coniferous and mixed forests. The southern part is mostly agricultural land with less than 10–15% forest cover. Soils are mainly podzol and allied types. The groundwater in most of the basin area is located at depths of 10–15 m and groundwater runoff plays an insignificant role in flood runoff generation. The snow season lasts for about 5 months with thaws seldom. During the snowmelt period from 30 to 70% of annual runoff is generated.

The model of runoff generation used is a modification the system of the physically-based models of hydrological processes developed in the Water Problems Institute (WPI) of the Russian Academy of Sciences (Kuchment *et al.*, 1986). The model includes simulation of the following processes: snow cover formation and snowmelt, freezing and thawing of soil, vertical moisture transfer and evaporation, surface water detention, overland, subsurface and channel flow. A finite-element schematization of the Vyatka River catchment area is used in the model.

To calculate the characteristics of snow cover, a system of vertically averaged equations of snow processes has been applied (Kuchment & Gelfan, 1996). The system includes a description of temporal change of the snow depth, content of ice and liquid water, snow density, snowmelt, sublimation, refreezing melt water, and snow metamorphism. Water and heat fluxes in the soil associated with phase transformation of water under soil freezing, thawing and infiltration of water are described by the system of partial differential equations described in Gelfan (2006). At the lower boundary of the podzol soil, where there is an impermeable layer, the vertical water flux is assumed zero. It is also assumed that the subsurface flow along the impermeable layer occurs if the soil moisture content exceeds the field capacity of soil. Cumulative melt water detention by the basin surface depressions, as well as the rate of evaporation from an unfrozen, snow-free soil, are calculated by the formulas presented in Kuchment *et al.* (1986). To describe overland and subsurface flow, the kinematic wave equations are applied. To calculate water movement through the river channels, the advection-diffusion equation is used. The subgrid variability of snow water equivalent and saturated hydraulic conductivity was taken into account by the methods described in Kuchment *et al.* (1986).

Most of the model parameters were determined using the available measurements of the basin characteristics of topography and river channels, soil and snow constants, vegetation measurements, and from the empirical relationships that were derived and tested using mainly Russian laboratory and field data. The parameter associated with snowmelt rate was adjusted through calibration against snow measurements separately for the open and forested areas. Four parameters (the speed of the flood wave propagation, the mean value of the free storage capacity before the beginning of melt, coefficient of the evaporation formula, and saturated hydraulic conductivity) were adjusted through calibration against observed hydrographs of 17 floods for the period from 1940 to 1959. The model validation was carried out by comparison of the observed and simulated hydrographs for the period from 1960 to 1980. The standard deviation of errors of the simulated flood volumes and peak discharges are equal to 9 mm and 486 m^3/s, respectively. The Nash and Sutcliffe efficiency criteria for the flood volume and discharge simulations are 0.94 and 0.84, respectively.

The weather generator was constructed using the meteorological measurements in the Vyatka River basin for 109 years (from 1881 to 1995). The weather generator structure was the same as in Kuchment & Gelfan (2002), but taking into account seasonal variations of the parameters of the precipitation model.

The Monte Carlo generated series of daily weather variables were used to simulate series of snowmelt runoff hydrographs in the Vyatka River. Using the simulated hydrographs, we constructed the synthetic series of the flood peak discharges and calculated the corresponding exceedance probabilities.

To assess the range of the uncertainty of the calculated exceedance probabilities associated with the weather generator inadequacy and insufficient lengths of the used series, we constructed their confidence limits under the assumption that the weather generator parameters are the normally distributed variables. For constructing confidence limits, we used the Monte Carlo procedure in conjunction with Latin hypercube sampling (LHS), generated 50 combinations of these parameters and calculated 1000 hydrographs for each combination. The flood peak discharge exceedence probabilities averaged over 50 1000-year series of the simulated hydrographs, the 95% confidence limits of the exceedance probabilities, and the exceedance probabilities estimated from the available series of the observed snowmelt flood peaks are shown in Fig. 1(a). The corresponding graphs for the Seim River basin are shown in Fig. 1(b). As can be seen from Fig. 1, the exceedence probabilities obtained from the series of simulated flood peaks correspond satisfactorily to the probabilities estimated from the observed series; however, the intervals of uncertainty visibly increase with decreasing exceedence probability.

USE OF THE PMD-ESTIMATES FOR REDUCTION OF UNCERTAINTY OF EXTREME FLOOD PROBABILITY

The largest floods in both the Vyatka River and Seim River basins are of snowmelt origin. Rain-on-snow events are rare in this region, and rains are moderate. Thus, the main problem in determination of the probable maximum flood is estimation of the probable maximum snowmelt (PMS) for the period, which is close to the time of concentration for the basin. We estimate the PMS under the following assumptions: (1) the sky during the snowmelt period is cloudless, (2) the net long-wave radiation and the evaporation from snow cover can be neglected during snowmelt period, (3) the heat input brought by rain water is small comparing with solar radiation, and (4) the rain water fully infiltrates into the snow pack.

In its general features, the applied procedure of maximization of snowmelt rate is close to one described by the US Army Corps of Engineers (1998). To calculate the maximum value of the turbulence exchange, the Kuzmin (1961) formula was used. As a result, PMS_{open} for an arbitrary day during the melt season was calculated for open (non-forested) areas by:

$$PMS_{open} = 0.26Q_0(1-\alpha_{\min}) + 4.86T_{\max}(0.18 + 0.098U_{\max}) \tag{1}$$

where PMS is the probable maximum snowmelt (in mm/d); Q_0 is mean daily short-wave radiation flux (W/m^2) under clear sky conditions; $\alpha_{\min}$ is minimum snow surface albedo under the conditions of intensive melt; $T_{\max}$ (°C) and $U_{\max}$ (m/s) are the maximum daily values of air temperature and wind speed for the day in question, respectively.

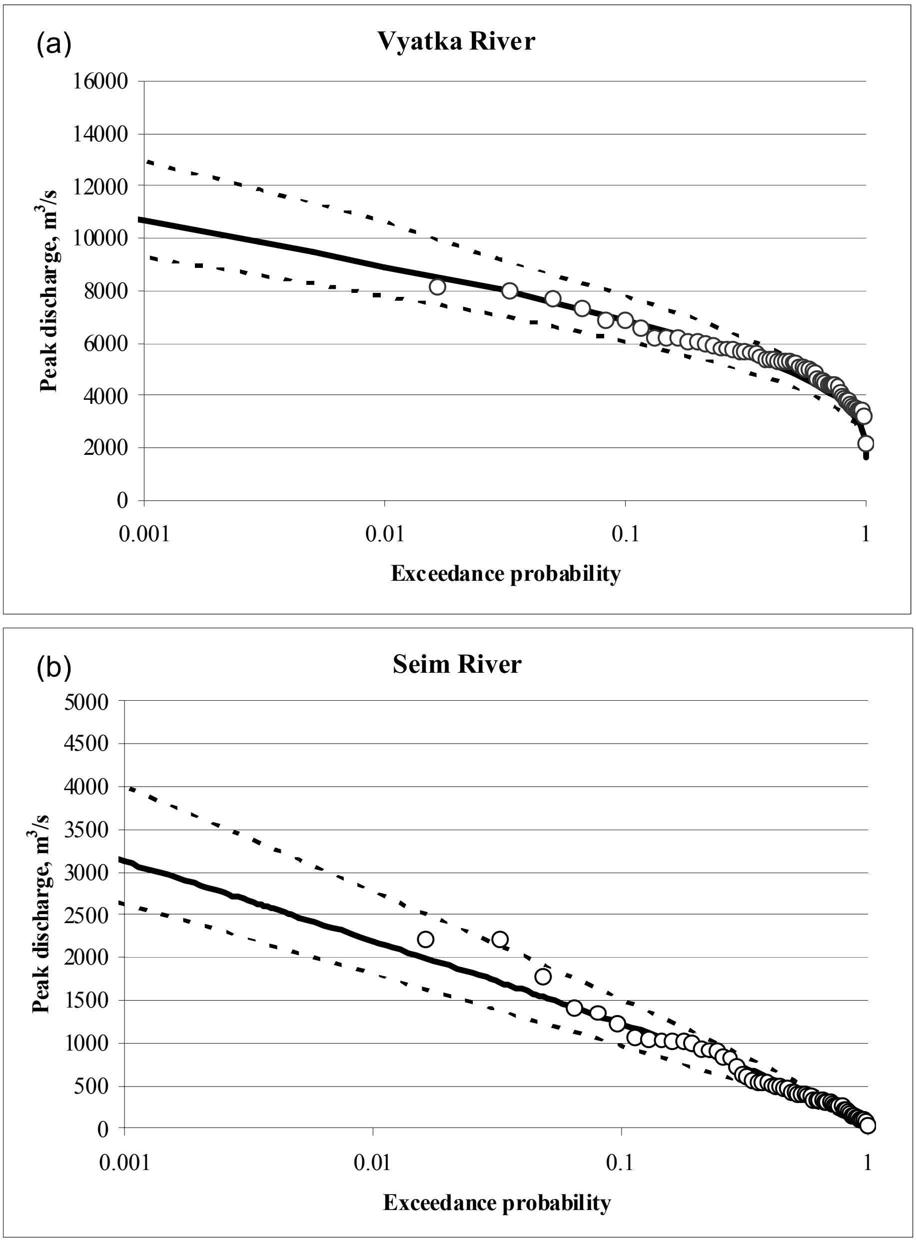

Fig. 1 Exceedance probabilities of the snowmelt flood peak discharges: calculated from the observations series (points), averaged over 50 1000-year series of hydrographs simulated by the dynamic-stochastic models (bold line). Dashed lines represent the 95% confidence intervals of the simulated exceedance probabilities.

The value of $\alpha_{\min}$ was assigned equal to 0.5; the values of $T_{\max}$ and $U_{\max}$ were determined from the available series of the meteorological observations.

The probable maximum snowmelt (PMS_{forest}) at the forest floor was assessed, taking into account reduction of short-wave radiation Q_0 and wind speed $U_{\max}$ calculated from the relationships presented in Gelfan *et al.* (2004).

As the probable maximum snow water equivalent before snowmelt (PMSWE), we used the maximum five-month total of precipitation estimated from WMO recommendations (WMO, 1973). The estimated PMSWE value turned out to be equal to 310 mm for the Vyatka River basin and 280 mm for the Seim River basin.

Using the value of PMSWE as the initial snow condition on the latest date of the beginning of snowmelt in the corresponding basin, we calculated the values of PMS_{open} and PMS_{forest} for each

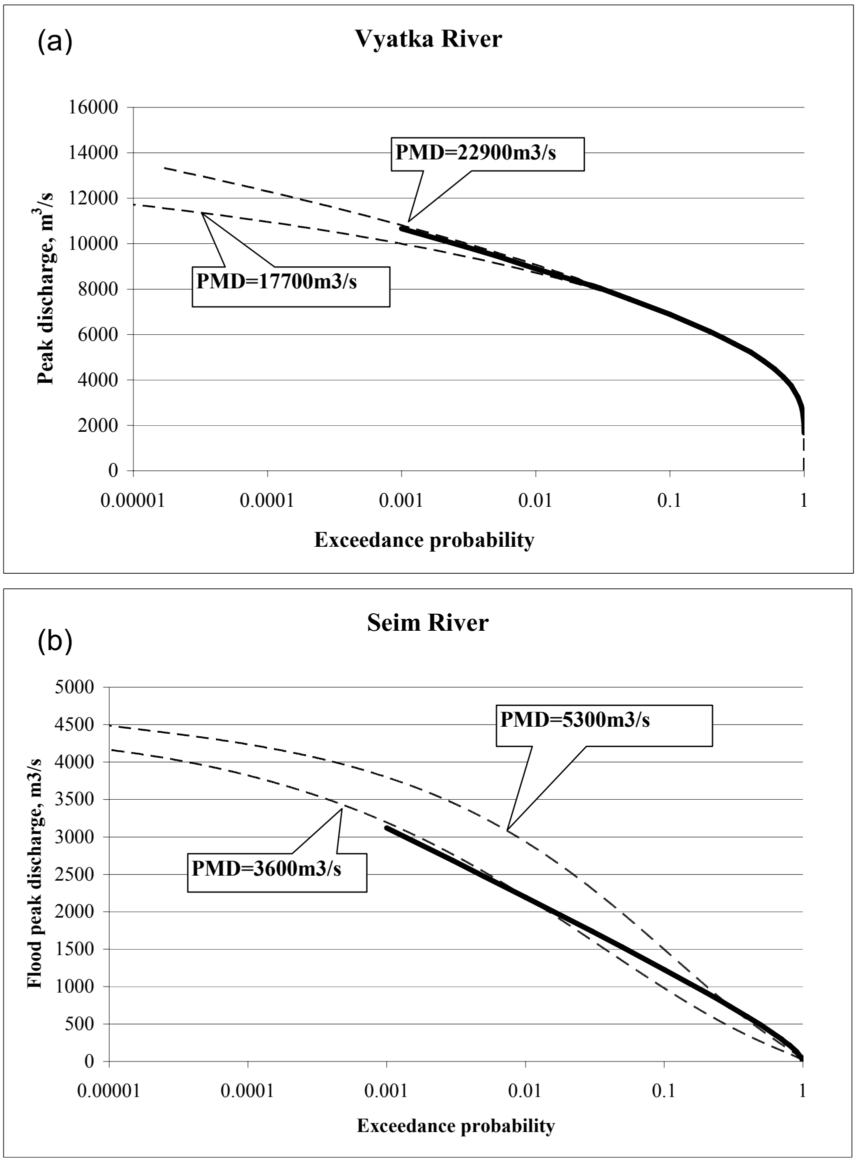

Fig. 2 Sensitivity of the Johnson S_B-distribution curves (dashed lines) to the assigned upper bound λ = PMD. Black line represents exceedance probability of the simulated flood peak discharge series.

day within the 10-day period after this date. For the Vyatka River basin, the calculated values of PMS_{open} and PMS_{forest} vary within 79–96 mm/d for open areas and 45–55 mm/d for forested ones during the period 21–29 April. For the Seim River basin, the calculated values of PMS_{open} vary within 70–89 mm/d during the period 4–13 April.

To calculate the probable maximum snowmelt flood (PMSF), we assumed that the runoff losses depend on the detention storage while infiltration losses equal zero. The PMSF hydrograph was simulated under this assumption and using probable maximum snowmelt as inputs. For the Vyatka River basin, the simulated PMD turned out to be 19 100 m^3/s (the maximum observed discharge was 8200 m^3/s in the spring of 1979). For the Seim River basin, the simulated PMD equals 4700 m^3/s, while the maximum observed discharge was 2230 m^3/s in the spring of 1928.

To approximate the exceedance probabilities of the simulated flood peak discharges Q shown in Fig. 1, the Johnson S_B-distribution function was applied. The probability density function of the Johnson S_B-distribution is written as (Hahn & Shapiro, 1967):

$$f(Q)=\frac{\eta}{\sqrt{2\pi}}\frac{\lambda}{(Q-\varepsilon)(\lambda-Q+\varepsilon)}\exp\left\{-\frac{1}{2}\left[\gamma+\eta\ln\left(\frac{Q-\varepsilon}{\lambda-Q+\varepsilon}\right)\right]^2\right\} \tag{2}$$

$$\varepsilon\le Q\le\lambda+\varepsilon;\ \eta>0;\ -\infty<\gamma<\infty;\ \lambda>0;\ -\infty<\varepsilon<\infty$$

where ε and $\lambda + \varepsilon$ are the lower and the upper limits of variations of Q, $\gamma = -1/C_v(\xi)$, $\eta = 1/\sigma(\xi)$, $C_v(\xi)$ and $\sigma(\xi)$ are the coefficient of variation and the standard deviation of $\xi = \ln[(Q-\varepsilon)/(\lambda+\varepsilon-Q)]$, respectively.

The lower limit ε of Q was naturally assumed to be equal to zero. The values of PMD = 19 100 m^3/s and 4700 m^3/s were utilized as the upper limits λ for both rivers. The other two parameters were estimated from the simulated flood peak discharge series using the method presented by Hahn & Shapiro (1967) and were equal to $\gamma = 2.66$, $\eta = 2.45$ for the Vyatka River simulated series and $\gamma = 0.86$, $\eta = 2.28$ for the Seim River simulated series. The Johnson S_B-distribution curves were constructed using the listed values of the parameters for both rivers and fitted to the corresponding simulated flood peak discharge series.

Taking into account that the simulated PMD can be determined with significant errors, we estimated the sensitivity of the obtained Johnson distribution curve to such errors which depended, first of all, on estimating $T_{\max}$ and $U_{\max}$ (equation (1)). Assuming that the errors in estimation of these values can reach ±50%, we obtained that PMD-estimates change within 17 700–22 900 m^3/s for the Vyatka River and within 3600–5300 m^3/s for the Seim River because of the errors in *PMS*. Figure 2 shows the Johnson S_B-distribution curves constructed using the obtained limits for the PMD-values and the exceedance probabilities of the simulated flood peak discharge series for both rivers. As can be seen from comparison of Fig. 1 and Fig. 2, the suggested procedure gave significantly more narrow intervals of the uncertainty in estimation of exceedance probabilities of flood peak discharges than using only the probabilistic approach.

CONCLUSION

The dynamic-stochastic simulation methodology, which is based on coupling a physically-based model with a stochastic weather generator, can provide an improvement in assessing the exceedance probabilities of extreme snowmelt flood peak discharges. However, it is possible to assume that the efficiency of the suggested methodology can be satisfactory up to the exceedance probability of 0.01–0.001 and, for more rare events, the errors can significantly increase because of the uncertainty caused by inadequacy of the stochastic models and shortness of the observed data series used for assigning the model parameters. This uncertainty may be decreased if the information given by the dynamic-stochastic simulation of peak discharges is combined with deterministic information in estimation of the probable maximum discharge (PMD) through the probable maximum snowmelt rate and a physically-based model of snowmelt runoff generation. The PMD value can be utilized as a parameter to fit the exceedance probabilities of flood peak discharges resulted from the dynamic-stochastic simulation by the Johnson S_B-distribution function.

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