International Water Resources Association
Water International, Volume 27, Number 1, Pages 77–86, March 2002

Estimation of Extreme Flood Characteristics Using Physically Based Models of Runoff Generation and Stochastic Meteorological Inputs

Lev S. Kuchment and **Alexander N. Gelfan**, *Water Problems Institute of Russian Academy of Sciences, Moscow, Russia*

Abstract: *There are two main schools of estimation of extreme flood characteristics in the world hydrological practice. The first approach is based on fitting a statistical distribution to available measurements of flood peak discharges and extrapolating this distribution to estimate the floods of needed low exceedance probabilities. The second one uses the concept of probable maximum flood. Neither approach practically utilizes available meteorological observations (that contain important information on possible variations of runoff generation) and both are based on implicit assumptions that the physical mechanisms of runoff generation do not depend on the magnitudes of the water inputs and land use changes. To overcome these shortcomings, a new technique based on coupling the Monte Carlo simulation of meteorological inputs with application of the detailed physically-based model of runoff generation processes is suggested. The paper illustrates the implementation of this technique for estimation of the extreme flood characteristics for the Seim River basin (the catchment area is 7,460 km^2). The model of runoff generation is based on the finite-element schematization of river basins and includes the description of snow cover formation and snowmelt, freezing and thawing of soil, vertical soil moisture transfer and infiltration, overland, as well as and channel flow. The Monte-Carlo simulation is based on stochastic models of daily precipitation series, daily air temperature and daily air humidity deficit (for continuous simulation during autumn-winter-spring seasons) or distributions of snow water equivalent, depth of frozen soil, and soil moisture content before snowmelt (for simulation during only spring period). The calculated exceedance probabilities of the flood peak discharge have been compared with ones calculated using long-term runoff data. As an example of the application of the developed technique, changes of the Seim River flood runoff characteristics resulting from changes of basin land use are given.*

Keywords: *Snowmelt flood; rainfall flood; physically based modelling; stochastic modelling; Monte Carlo simulation.*

Introduction

Estimation of extreme flood characteristics is a classic hydrological task associated with flood risk assessments, design of flow control constructions, and dam safety evaluation. Increasing demands for the acceptable potential economic and environmental risk in water resources management have necessitated improving reliability of the existing methods of estimation of extreme flood characteristics and developing such methods for flood events of very low probabilities. At the same time, the solution of this task has been made more complicated because of intensification of human activity on the river watersheds and climate change.

In present-day hydrologic practice, there are two main approaches to estimation of extreme flood characteristics. The first approach is based on frequency analysis of measured flood peak discharges, fitting a chosen statistical distribution to these values, and extrapolating this distribution for determination of the peak discharges of needed low exceedance probabilities. The methods using this approach are well-developed and widely tested; however, as it has been shown in many papers (for example, Swain et al., 1998), this approach yields reliable estimates of flood peak discharges if the recurrence intervals of these discharges do not significantly exceed the lengths of measured peak discharge series. Additionally, for the solution of many hydrological and environmental problems it is important to know not only the maximum flood peak discharges but also the maximum flood hydrographs.

The second approach is based on an assumption that there are some maximum values of precipitation for each region and for each season, and these values can be utilized for calculation of the hydrographs of the probable maximum floods (PMF) with the aid of the unit hydrograph method or conceptual runoff generation models. The techniques for estimating the probable maximum precipitation values have inadequate scientific foundation and usually give maximum floods that have never reached up. Bowles et al. (1994) have found a significant difference between the PMF estimates based on the different assumptions on centering, orientation, storm area, and position of the peak interval of the probable maximum storm. At the same time, the absence in the PMF-approach the estimation of the probabilities of the possible maximum discharges creates the difficulties for decision-makers who prefer to have probabilistic estimates of the possible flood characteristics together with assessment of available uncertainty.

It is worth noting that neither of the aforementioned approaches fully utilizes the available meteorological observations that contain important information on possible variations of runoff generation processes. Another common shortcoming of these approaches is implicit assumptions that the physical mechanisms of runoff generation do not depend on the magnitudes of the water inputs and the drainage basin characteristics are not change in time in spite of possible human activities and climate change. However, many hydrological processes are essentially nonlinear, and the physical mechanisms of extreme flood generation are often quite different from such mechanisms for usual floods. In many cases, the extreme floods can be a result of such unusual combinations of hydrometeorological factors and runoff generation mechanisms that may be unobserved in the historical data. In a number of regions, the extreme floods may be of snowmelt or mixed snowmelt-rainfall origin. Human activity (for example, deforestation, urbanization, change of land use) may have a significant influence on the generation of extreme floods may have.

Achievements in development of the physically-based models of runoff generation and stochastic analysis of meteorological time series as well as an immense increase of the computer facilities enable implementation of new methods for estimating the extreme flood characteristics and that provides possibility to overcome, to significant extent, the shortcomings of both approaches mentioned above. This new technique may be constructed on simulation of possible runoff hydrographs by means of coupling stochastic models of meteorological inputs and runoff generation models (the dynamic-stochastic models of runoff generation).

Eagleson (1972) was probably the first who employed a dynamic-stochastic model of runoff generation for calculation of statistical characteristics of maximum runoff from the statistical characteristics of rainfall but trying to apply only analytical solutions of the underlying differential equations he implemented oversimplified process description. The development of Eagleson's method and its application to practical tasks of calculating maximum discharges due to rainfall and snow melting are described by Wood and Harley (1975); Carlson and Fox (1976); Chan and Bras (1979); Hebson and Wood (1982); Diaz-Granados et al. (1984).

Kuchment and Gelfan (1991) first combined the simulation of meteorological inputs by the Monte-Carlo method with the numerical solution of the differential equations describing runoff generation processes. It essentially widens the opportunities of application of the complicated nonlinear models of runoff generation and the complex stochastic models of meteorological inputs. However, in (Kuchment and Gelfan, 1991), because of the limitations of the computer facilities, a relatively simple dynamic-stochastic model of rainfall and snowmelt runoff generation was applied. Calver and Lamb (1995) estimated flood frequencies with the aid of the Monte Carlo simulation of meteorological inputs using two conceptual semi-distributed models of runoff generation. Salmon et al. (1997) and Cattanach et al. (1997) applied the Monte Carlo simulation of meteorological inputs for estimating frequencies of extreme floods on the basis a conceptual model of runoff generation, probability distributions of rainfall and snow melt, and antecedent soil moisture content. Cameron et al. (1999) used Monte Carlo simulation to estimate uncertainty of flood frequencies derived from rainfall stochastic model coupled with the TOPMODEL.

Opportunities of development of the dynamic-stochastic models of runoff generation for estimating extreme flood characteristics are associated, first of all, with choice of the relevant model structure. Conceptual models of runoff generation that are commonly used in hydrological practice (SSARR, HEC1, Sacramento, NWSRFS, HSPF, etc.) contain aggregated empirical parameters that may have unclear physical meaning and exhibit a large range of variation. As a result, these models after calibration may give a satisfactory accuracy for conditions that are close to observed events and used for construction and calibration of the models. However, the reliability of these models in unusual hydrometeorological conditions or at changing basin characteristics can be very low. In contrast, physically-based models include parameters with clear physical meaning and values of these parameters can, in principle, be determined from direct measurements in a given watershed or from *a priori* information gained from laboratory or field investigations in similar physiographic conditions. These models use more information available on drainage basin characteristics and simplify the prediction of runoff change caused by human activity on the drainage basin area. Thus, coupling the detailed physically based models of runoff generation with the Monte–Carlo procedure of simulation of meteorological inputs permits estimating exceedance probabilities of peak discharges and volumes of floods for the most severe combinations of meteorological and hydrological conditions, taking into account the nonlinearity of hydrological processes and the change of drainage basin characteristics.

The input data for flood generation models include the time series of precipitation, air temperature, air humidity, as well as solar radiation and wind speed for the snowmelt period. Consequently, for continuous Monte-Carlo simulation of these values during the whole year it is necessary to have their stochastic temporal models. Because of the strong and seasonally-changed autocorrelation and crosscorrelations commonly existing in the meteorological time series, construction of such models is a complicated task and many such models may be too sophisticated and unreliable for application in the estimation of flood characteristics of small exceedance probabilities, especially extreme values. Each run of runoff simulation with the aid of the distributed physically based model requires a significant computer time and it is necessary to choose the models as simple as possible. The optimum structure of the dynamic-stochastic model depends on climatic conditions, main hydrological processes, and available hydrometeorological information. As an example, illustrating the proposed approach, we shall consider constructing the dynamic-stochastic model of extreme flood generation for the Seim River basin.

Choosing and Construction of the Physically Based Model of Flood Generation

The Seim River basin (the catchment area to Kursk is 7,460 km^2) is a part of the Dnieper River basin. The relief of the basin is a rugged plain with many river valleys, ravines, and gullies. The soils are mainly chernozem, grey forest soil, and meadow soil. The groundwater level fluctuates at 15 to 20 m below the land surface. The largest part of the basin (about 70 percent) is ploughed, the forest occupies about 10 percent, the pastures and urbanized land take up about 20 percent. The mean annual precipitation is 600 to 650 mm, the mean snow water equivalent before melt is 85 mm. The mean snowmelt runoff is 55 mm; the mean peak discharge is 592 m^3/s, and their coefficients of variation are, respectively, 0.43 and 0.81. The mean snowmelt peak discharge is almost 20 times higher than the rainfall one.

To choose an optimum structure of the extreme flood generation in a chosen river basin, the system of the physically-based models of hydrological processes developed in the Water Problems Institute (WPI) of the Russian Academy of Sciences was applied (Kuchment et al., 1983; 1986; 1990). The WPI system provides simulation of a wide diversity of runoff generation mechanisms for exploring different assumptions about runoff generation mechanisms for a given basin and choosing the optimum structure of the whole model of runoff generation for this basin. The WPI model system can simulate the following processes which can results in extreme floods and which are poorly described by the commonly used conceptual models:

- unsteady overland flow and river channel flow at the flow depths, which had not been reached during the floods for the period of runoff measurements (overbank flow, flow at sharply changed hydraulic characteristics);
- formation of impermeable soil layer at different depths as results of thermophysical processes during winter and spring periods;
- formation of ice crust;
- runoff generation at the rainfall on the snow cover;
- interaction of subsurface and overland flow;
- change of the contributed area depending on the rainfall characteristics.
- change of the land use of the drainage area (urbanization, forest cutting, land treatment).

Most of the model constants can be determined from usually available measurements of the drainage basin characteristics (relief and river channel characteristics; soil constants, snow measurements) and from empirical ratios that were derived and tested using mainly the Russian laboratory and field data. Part of the parameters can be calibrated using the available measurements of hydrological variables: runoff, snow cover, soil moisture, and evaporation.

As a result of an analysis of data of hydrometeorological measurements and numerical experiments, the following structure of the runoff generation model the Seim River basin was chosen.

Snow Cover Formation and Snowmelt

To calculate the characteristics of snowpack, the system of vertically averaged equations of snow processes in a point has been applied (Kuchment and Gelfan, 1996; Kuchment et al., 2000). The system includes the description of temporal change of the snow depth, content of ice and liquid water, snow density, snowmelt, sublimation, refreezing melt water, snow metamorphism.

Soil Freezing

The soil freezing is described by the following equations (Kuchment, 1980; Kuchment and Gelfan, 1993):

$$C_f \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\lambda_f \frac{\partial T}{\partial z}\right), \quad 0 < z < H(t) \tag{1}$$

$$C_{uf} \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\lambda_{uf} \frac{\partial T}{\partial z}\right), \quad H(t) < z < L \tag{2}$$

$$T(0,t) = T_0(t); T(H,t) = 0; T(L,t) = T_L; T(z,0) = T(z) \tag{2a}$$

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(D_f \frac{\partial \theta}{\partial z} - K\right), H(t) < z < L \tag{3}$$

$$\theta(L,t) = \theta_L; \theta(H) = \theta_0; \theta(\mathrm{z},0) = \theta(\mathrm{z}) \tag{3a}$$

$$\lambda_f \frac{\partial T}{\partial z}\Big|_{z=H-0} = \lambda_{uf} \frac{\partial T}{\partial z}\Big|_{z=H+0} + \chi \rho_w (\theta_- - \theta_0) \frac{dH}{dt} \quad (4)$$

$$H(0) = 0 \quad (4a)$$

where $H(t)$ = depth of frozen soil at time t; $T(z,t)$ = soil temperature at the depth z and time i; λ_f, and λ_{uf} = thermal conductivities of frozen and unfrozen layers of soil, respectively; C_f and C_{uf} = heat capacities of frozen and unfrozen layers of soil, respectively; χ = latent heat of ice fusion; $\theta(z,t)$ = volumetric liquid water content of unfrozen soil; θ_- = liquid water content just above the freezing front; θ_0 = liquid water content at a temperature near 0^oC (assumed to be equal to the wilting point); D_f = diffusivity of soil moisture; K = hydraulic conductivity; and L = depth of the ground where the ground temperature and the volumetric moisture content can be considered as constants equated T_L and θ_L, respectively (L was taken to be equal to 2 m). The temperature T_0 of the soil surface is calculated from

$$\lambda_s \frac{T_a - T_0}{H} = -\lambda_f \frac{\partial T}{\partial z}\Big|_{z=0} \quad (5)$$

where H_s and λ_s are snow depth and thermal conductivities of snow, respectively; and T_a is temperature of air.

The Equation 3 describes soil moisture transfer from the unfrozen layer of soil to the freezing front. According to experimental data (see Kuchment and Gelfan, 1993; and references therein), this process plays an important role in the vertical redistribution of soil moisture during the cold period for soils which are typical for forested-steppe zone.

The diffusivity, the hydraulic conductivity of unfrozen soil, the heat capacities and the thermal conductivities of frozen and unfrozen soil were calculated by the formulas from (Kuchment et al., 1983; Kuchment et al., 2000).

An implicit four-point finite difference scheme was used for the numerical integration of the equations of heat and moisture transfer; the corresponding system of difference equations were solved by the double-sweep procedure.

Soil-thawing

Soil-thawing was calculated for snow-free areas of the catchment area from the end of snowmelt. The movement of the soil-thawing front was described by the equations similar to ones used for soil freezing description excluding Equation 3. The description of soil thawing model has been presented in (Kuchment, et al., 2000).

Meltwater Infiltration into Frozen Soil

It was assumed that melting water saturates the upper layers of soil just after the beginning of snow melting; so the intensity of infiltration into the frozen soil was assigned equal to the saturated hydraulic conductivity of the frozen soil K_f calculated as (Kuchment and Gelfan, 1993):

$$K_f = K_{uf} \left(\frac{P - I - \theta_0}{P - \theta_0} \right)^4 \frac{1}{(1+8I)^2} \quad (6)$$

where K_{uf} = saturated hydraulic conductivity of unfrozen soil; P = volumetric porosity; and I = volumetric ice content of the upper layer of soil.

Detention of Melt Water by Basin Storage

It was assumed that the spatial distribution of the free storage capacity D before snow melting can be described by exponential probability function. In this case, the sum detention of water D_R by the basin storage up to time t after the beginning of melting was determined as (Kuchment and Gelfan, 1993):

$$D_R = \int_0^R [1 - F(D)] dD = D_0 \left[1 - \exp\left(-\frac{R}{D_0} \right) \right] \quad (7)$$

where

$$F(D) = 1 - \exp\left(-\frac{D}{D_0} \right);$$

D_0 = expected value of the free storage capacity (or the maximum possible detention); and

R = sum melt and rainfall water yield on the basin area up to time t

The Vertical Movement of Water in the Unfrozen Soil

The changes of the unfrozen soil moisture content and infiltration into the soil during the warm period were calculated by the Equation 3.

The evaporation rate E calculated as (Kuchment and Gelfan, 1993):

$$E = k_E d_a(t) \theta(0,t) \quad (8)$$

where d_a = air humidity deficit; and k_E = empirical constant.

Overland and Channel Flow

Overland flow is the main mechanism of snowmelt runoff generation for the Seim River basin. Subsurface contribution into the total runoff during spring flood period is negligible. To model overland and channel flow, the one-dimensional kinematic wave equations were applied (Kuchment et al., 1986). For numerical integration of these equations, the finite element method was used. The finite element schematization of the drainage area and the struc-

Figure 1. Finite element schematization of the Seim River basin: 1-subcatchment boundaries; 2-channel network; 3-runoff gauge stations; 4-agrometerological stations.

ture of the river network (Figure 1) was carried out taking into account the river basin topography, soils, land use, and vegetation.

Calibration and Verification of the Model

To calibrate and verify the model of runoff generation of the Seim River basin, daily meteorological data measurements during 20 years (1969 to 1988) were used. A set of numerical experiments had been carried out to estimate the sensitivity of the runoff hydrographs to change of different parameters of the model before calibration. The sensitivities of flood peak discharges to five main parameters are shown in Figure 2. It has been revealed that the saturated hydraulic conductivity and the degree-day factor are the most important. The first parameter controls runoff losses and the second one determines meltwater outflow from snowpack. The influence of routing parameters (Manning's coefficients of roughness for the slope surface and the river channels) on flood peaks is not too strong. The parameter of the maximum possible water detention D_0 essentially influences on flood generation only during a short time at the beginning of melting. All these

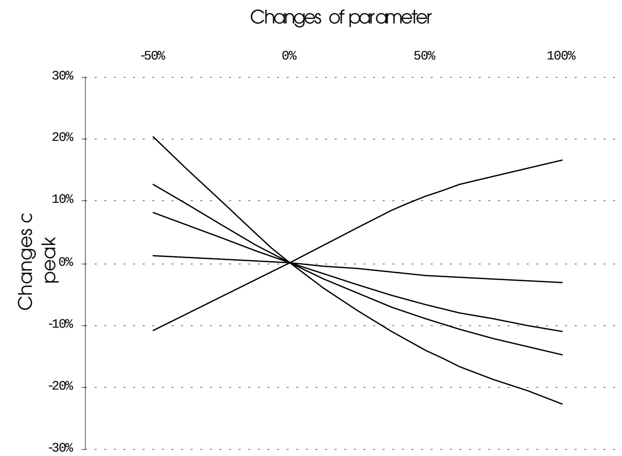

Figure 2. Sensitivity of the calculated peak discharges to changes of the calibrated parameters of the model (1 – the maximum possible water detention; 2 – Manning roughness coefficient for overland flow; 3 - Manning roughness coefficient for river channel flow; 4– saturated hydraulic conductivity; 5 – degree-day factor).

five parameters were calibrated against measured runoff hydrographs for the period 1969 to 1978.

The rest of the parameters were assigned on the basis of the available data measurements at four agrometeorological sites located within the watershed area. The list of the parameters utilized by the model is shown in Table 1.

Table 1. Parameters of the Model of Runoff Generation in the Seim River Basin

Physical Meaning of the Paramete	*Numerical Value*
Measured Constants	
Density of soil	1,100 kg m^{-3}
Density of the soil matrix	2,500 kg m^{-3}
Volumetric porosity of soil	0.5
Wilting point of soil	0.14
Maximum hydroscopicity of soil	0.07
The field capacity of the soil	0.32
Constants Assigned Using Experimental Data	
Specific heat capacity of soil matrix	1,100 j kg^{-1}
Matrix potential of soil at maximum hydroscopicity	-550 m
Snow refreezing rate	$6x10^{-8}$m s^{-1}°C^{-1}
Snow compression parameter	$3x10^{-7}m^2s^{-1}kg^{-1}$
Evaporation rate parameter	$2x10^{-9}$m $mb^{-1}s^{-1}$
Parameters Calibrated Using Measured Hydrographs	
Free storage capacity before snowmelt	0.01 m
Saturated hydraulic conductivity of soil	0.001 m s^{-1}
Manning's coefficient of roughness for the slope surface	0.15 s $m^{-1/3}$
Manning's coefficient of roughness for the river channels	0.07 s $m^{-1/3}$
Degree-Day factor	2.5x10-10 $^{m4°}C^{-1}kg^{-1}s^{-1}$

The verification of the model was performed by comparison of the measured and calculated hydrographs for the period of 1979 to 1988. Comparison of these hydrographs is given in Figure 3. The measured and calculated flood peak discharges during the whole data set (20 years) are compared in Figure 4. As can be seen from these figures, the developed model of runoff generation gives a satisfactory simulation of the Seim River hydrographs.

Stochastic Input Models and Estimating the Exceedance Probabilities of Flood Peak Discharge

To simulate the meteorological inputs, models of precipitation, daily air temperature for cold season (from November 1 to April 30), and air humidity deficit for warm season (from May 1 to October 31) were applied. To choose the structure and to determine the parameters of

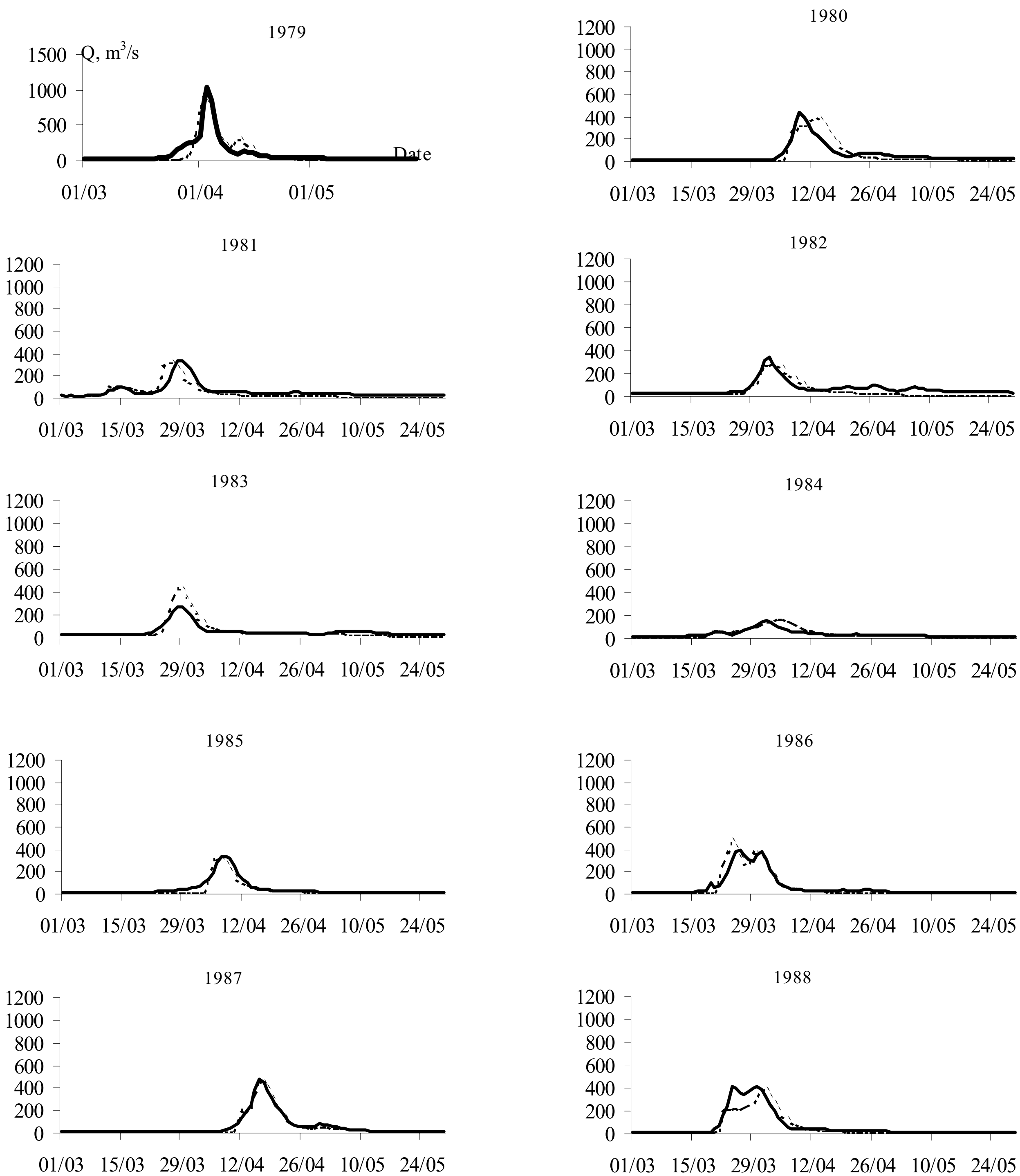

Figure 3. Observed (bold line) and calculated (dashed line) hydrographs of the Seim River (verification phase).

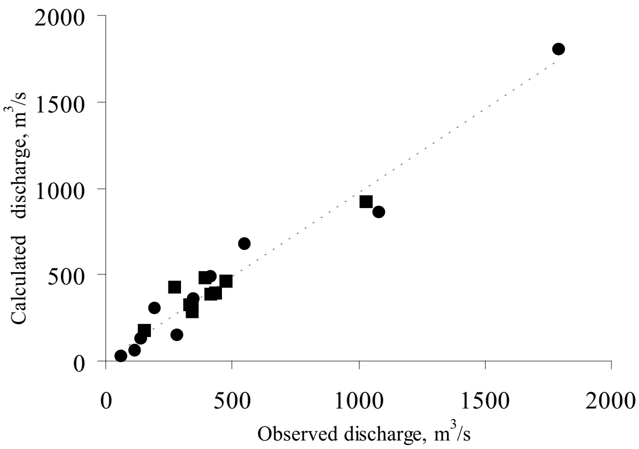

Figure 4. Observed vs. calculated snowmelt flood peaks: circles – calibration period (1969 to 1978); squares – verification period (1979 to 1988).

these models, the meteorological measurements at a station, located in the center of the Seim River basin for 101 years (1891, 1892, 1896–1941, 1943–1995) were used.

The precipitation model consists of a model of daily precipitation occurrence (a first-order Markov chain is applied) and a gamma distribution of daily precipitation amounts. Parameters of the distribution were determined separately for the warm and cold seasons.

Because of the strong auto-correlation in the air daily temperature series, the following approach was applied for modeling the daily temperature. At first, the observed sequences of daily air temperature for cold seasons were divided by their average values to obtain the normalized series "fragment" for each season. Then these series were separated into several groups taking into account a range of change of the average temperature. The distribution of the average seasonal temperature was fitted by the normal probability distribution. For generation of synthetic temperature series, a random value of the average seasonal temperature was generated and multiplied by the "fragment" randomly chosen from the corresponding group.

The histogram of daily air humidity deficit values was fitted by lognormal distribution. It was assumed that in the wet days the humidity deficit is negligible. The list of the parameters utilized by the stochastic models is shown in Table 2.

We tested two procedures of simulation of possible flood events. In the first procedure, we used the Monte Carlo simulations to construct the continuous series of meteorological inputs (a wet-dry day sequence is generated each year, daily precipitation for each wet day, daily air humidity deficit for each dry day, and daily air temperature for each period from November 1 to April 30) and then to calculate possible spring-summer floods.

In the second procedure, we tried to avoid long-period stochastic modeling of meteorological inputs before snowmelt. To do so, we at first used the available series of measured daily air temperature, air humidity deficit, and precipitation for the period from May 1 to March 1 for 34 years in order to calculate the soil moisture content, the depth of frozen soil, and the snow water equivalent before the beginning of snowmelt for each year. Then the empirical probability distributions of these values are constructed and fitted by gamma-distributions. These distributions were used for the Monte Carlo simulation of different combinations of the initial conditions in the river basin before snowmelt. At last, the combinations of the initial conditions together with the Monte Carlo simulation of meteorological inputs during spring-summer period were applied for flood simulation.

Table 2. Parameters of the Stochastic Models of Meteorological Inputs

Meaning of the Parameter	*Numerical Value*
Precipitation Model	
Tranisition probability matrix*	P_{oo}=0.7 P_{01}=0.3 P_{10}= 0.4 P_{11}=0.6
Mean of daily precipitation amount for warm period	4.7 mm/day
Mean of daily precipitation amount for cold period	2.5 mm/day
Standard of daily precipitation amount for warm period	6.6 mm/day
Standard of daily precipitation amount for cold period	3.8 mm/day
Air Temperature Model	
Averaged mean of seasonal temperature	4.0°C
Standard of mean of seasonal temperature	2.0°C
Air Humidity Deficit Model	
Mean of daily air humidity deficit	7.5mb for wet days 0.0 mb for dry days
Standard of daily air humidity deficit	1.7 mb for wet days 0.0 mb for dry days

P_{00} means probability of dry day after dry day; P_{10} means probabilty of dry day after wet day P_{01}=1-P_{00} P_{11}=1-P_{10}

Both procedures were applied and used to calculate the runoff hydrographs and the peak discharges with the aid the model runoff generation.

Figure 5 shows the comparison of the exceedance probabilities of snowmelt flood peaks calculated from 61-year measurement data and the exceedance probabilities determined from the 20,000 snowmelt hydrographs obtained on the basis of Monte-Carlo modelling of input data by the both procedures considered above.

Table 3 gives the comparison of the statistical characteristics of the flood peak discharges, calculated from available 61 years (1928 to 1940; 1943 to 1990) series of hydrological measurements, from the 20 years series of hydrological measurements (data used for calibration and

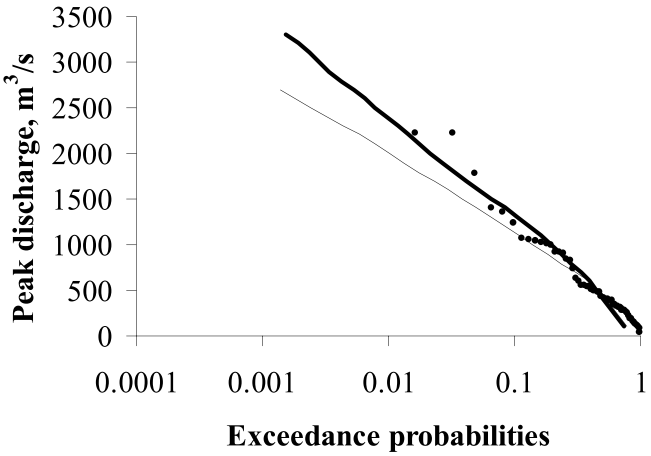

Figure 5. Exceedence probabilities of the snowmelt peak discharges of the Seim River: circles - 61-year series of the obseved peaks; fine line - calculations by the dynamic-stochastic model with random meteorological inputs; bold line - calculations by the dynamic-stochastic model with random initial conditions.

verification of runoff generation model), and from the 20,000 snowmelt hydrographs obtained on the basis of synthetic input data. As can be seen from Table 3 and from Figure 5, the correspondence between the observed statistical characteristics and calculated on basin of the Monte-Carlo simulation is quite satisfied.

The mean value of snowmelt peak discharge calculated by the first procedure appears to be closer to the observed mean than one calculated by the second procedure. However, the coefficient of variation of flood peaks and the quantilies of low exceedance probabilities calculated by the second procedure are closer to the corresponding values obtained by the 61-year observation series. It is possible to assume, that the first procedure allows us to reproduce better the averaged conditions of snowmelt runoff generation, but not conditions of the extreme floods generation. Perhaps, using the second procedure, we can determine more reliable low exceedance probabilities.

It is seen from the Table 3 and Figure 5 that both procedures give flood peak statistical characteristics, which are closed to ones treated from the longest observations series. This result is obtained despite the fact that the calculations were made applying the runoff data series three time shorter than the longest one.

Changes of Exceedance Probabilities of Flood Characteristics at Changing Basin Land Use

The model is applied for estimating exceedance probabilities of flood characteristics at three scenarios of land use in the Seim river basin (for the beginning of the twentieth century, for the present time, for future). The main difference in these land use scenarios associated with change of area of agriculture land and agriculture land treatment. At the beginning of the last century, the all agriculture land used after harvesting as a pasture. At the present time, only about 20 percent of agricultural land (about 70 percent of the basin area) is used for grazing after harvesting. The forest and virgin land areas did not change during last century. However, it is supposed that in future the present virgin land area will be used for agriculture and deep ploughing will be used for all agricultural area. The main change of the soil characteristics is revealed in change of the saturated hydraulic conductivity K_{uf} and the free storage capacity D_0. As can be seen from Table 4, the decrease of mean value of flood peaks during XX centure is about 12 percent; the coefficient of variation of peak increased from 0.77 to 0.84. The ploughing of the present-day virgin lands can decrease the present-day mean flood peak from 644 m^3/s to 554 m^3/s. The coefficient of variation of flood peak will increase from 0.84 to 0.91. The flood peak discharges of low exceedance probabilities will change relatively less than peaks of small and moderate floods.

Table 3. Statistical Characteristics of the Measured and Calculated Flood Peak Discharges of the Seim River

	Mean $m^3/8$	*Standard Deviation, m^3/s*	*Coefficient of Variation*	*Quantilies of Different Exceedance, Variation Probabilities, m^3s*				
				0.001	*0.005*	*0.02*	*0.05*	*0.1*
				Measurement Data				
61 years	592	483	0.81	-	-	2,230	1,790	1,240
20 years	458	409	0.89	-	-	-	1,790	1,080
				Calculated Data				
First Procedure	619	472	0.76	2,789	2,260	1,758	1,411	1,136
Second Procedure	644	541	0.84	3,460	2,726	2,043	1,625	1,328

Table 4. Statistical Characteristics of the Flood Peak Discharge at Different Land Use in the Seim River Basin

Land Use	*Parameter Values*	*Mean m^3s*	*Coefficient of Variation*	*Quantities of Different Exceedance Probabilities, m^3s*		
				0.002	0.005	0.010
Ploughing after grazing - 70% Virgin land - 20% Forest - 10% (beginning of XX century)	K_{uf}=50 cm/day D_0= 8 mm	735	0.77	3,270	2,820	2,494
Ploughing after grazing - 20% Autumn deep ploughing - 50% Virgin land - 20% Forest - 10% (present)	K_{uf}=90 cm/day D_0= 12 mm	644	0.84	3,187	2,726	2,395
Autumn deep Ploughing - 90% Forest - 10%	K_{uf}= 130 cm/day D_0= 18 mm	554	0.92	2,980	2,505	2,155

Conclusions

The Monte-Carlo simulation of runoff hydrograph based on the physically based models of runoff generation and the stochastic models of meteorological inputs can ensure a more reliable determination of the statistical distributions of runoff characteristics than the statistical analysis of short observed runoff series. This technique can be applied to estimate change of flood characteristics resulted from change of land use. However, there are significant difficulties in assigning parameters of the models of runoff generation and in constructing the stochastic models of meteorological models. For further improvement of this technology, it is necessary to develop the methods of estimation of uncertainty in constructing models and input data.

Acknowledgements

The present work was carried out as part of a research project supported by the Russian Foundation of Basic Researches.

About the Authors

Lev S. Kuchment has held the position of Head of the Laboratory of the Hydrological Cycle at the Water Problems Institute of the Russian (formerly USSR) Academy of Sciences, Moscow, since 1977. Professor Kuchment is the author of 170 scientific publications, including seven books. He is an expert in the modeling of hydrological processes and application of these models in hydrological forecasting and design. His research interests have included: snow cover formation; heat and moisture transfer in soil; evapotranspiration; overland, subsurface and groundwater flow; interaction of surface water and groundwater; unsteady flow in river channel systems; water quality formation; the hydrological cycle as a whole. He has also dealt with estimation of human-induced changes of the hydrological cycle and possible hydrological impacts of global climate change. In recent years, his main research fields are risk assessment of catastrophic floods. He can be contacted at the Water Problems Institute of Russian Academy of Sciences, Gubkina 3, 119991, Moscow, Russia. Email: kuchment@mail.ru.

Dr. Alexander N. Gelfan has been working in the Laboratory of the Hydrological Cycle at the Water Problems Institute, Russian Academy of Sciences in Moscow, since 1986. He has published 28 papers and one book in hydrology. His research interests include physically-based modelling processes of runoff generation, extreme flood modelling, flood-frequency prediction using dynamic-stochastic models, predicting the effects of land use and climate changes on floods. He has also dealt with modelling hydrological processes in permafrost regions. He can be contacted at the Water Problems Institute of Russian Academy of Sciences, Gubkina 3, 119991, Moscow, Russia. Email: a_gelfan@hotmail.com.

Discussions open until September 1, 2002.

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