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WATER RESOURCES AND THE REGIME OF WATER BODIES

Analysis and Simulation of Rain Flood Hydrographs in Belarus Rivers

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Abstract—Flood formation conditions in Belarus rivers in different seasons are considered. Hydrographs of rain floods are analyzed. A procedure is proposed for the construction of rain flood hydrographs in the absence of data of hydrometric observations with refinement and simplification of some calculations and improvement of the reliability of flood runoff characteristics.

Keywords: rain flood, hydrograph, recurrence, factors

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INTRODUCTION

Water regime of Belarusian rivers at the annual scale shows high spring flood, relatively low summer period, and occasional floods. Water abundance in autumn and winter is commonly relatively high because of considerable precipitation. Two peaks (spring and autumn) and two minimums (summer and winter) can be identified in the annual runoff distribution. The spring runoff accounts for 44–67% of the annual value.

Floods in Belarus rivers are almost annual, occurring in different seasons. Rain floods account on the average for 15–20% (in individual years, 40% and more) of the annual river runoff. The maximal discharges during rain floods can be higher than spring floods peaks. This is most typical of the basins of the Pripyat, Zapadnyi Bug, and Viliya. Since the mid-1980s, the number of cases with rain floods exceeding spring floods tends to increase in all rivers of the countries.

The solution of practical problems (designing reservoirs and ponds, assessment of floodplain inundation, the passage of high water via road structures, the development of measures for flood control, water drainage from structures during their construction, etc.), in addition to peak discharge, requires data on the duration of floods, and the rate of their rise and recession. The time distribution of flood is described by rain flood hydrographs.

The objective of this study is to analyze and simulate rain flood hydrographs in rivers of Belarus in the cases where there are little if any hydrometric observation data. The problem of determining flood characteristics in such cases is among the most important. Thus, only 123 gauges are in operation in Belarus on more than 20 thousand rivers and creeks. The current procedure for constructing rain flood hydrographs in the absence of hydrometric observation data on rivers implies the existence of rivers–analogs. However, it is difficult to find a river–analog, considering the sparse gauge network. In addition, the current changes in the runoff formation conditions (because of the increasing anthropogenic load and climate changes) make it necessary to improve the existing methods of calculating hydrological characteristics.

INPUT DATA AND METHODS OF STUDIES

The study was based on the observational data collected by the Department of Hydrometeorological Activity, Ministry of Natural Resources and Environmental Protection, the Republic of Belarus, including data on maximal water discharges during rain floods in the period from the beginning of instrumental observations to 2010, mean daily water discharges in rivers in period 1981–2010, and daily precipitation from weather stations in period 1960–2010.

Current regulatory documents recommend calculating single-humped hydrographs of rain floods in the absence of hydrometric observation data for the conditions of Belarus by a method proposed by G.A. Alekseev. The formula for calculating a single-humped hydrograph has the form [5]:

$$y = 10^{-\frac{a(1-x)^2}{x}}, \quad (1)$$

where $y = \frac{Q_i}{Q_P}$ is the ratio of water discharge Q_i to the maximal mean daily discharge Q_P with a specified recurrence P, %; $x = \frac{t_i}{t_\mathrm{f}}$, expressed in terms of shares of flood rise duration t_f, here t_i is the time corresponding Q_i from the beginning of the flood; a is a parameter, depending on the coefficient of hydrograph shape λ:

$$\lambda = \frac{qt_\mathrm{f}}{0.0116h} \quad (2)$$

(q is the module of maximal mean daily discharge of rain flood, $m^3/(s\ km^2)$; t_f is the duration of flood rise, day; h is runoff depth over the flood, mm).

The coefficient of hydrograph shape λ, the abscissa of the calculated hydrograph x, and the ordinate y are taken depending on the coefficient of asymmetry of hydrograph k_s, evaluated by the following formula ([5], Appendix B, Table B.10):

$$k_s = \frac{h_\mathrm{f}}{h} = f(\lambda), \quad (3)$$

where h_f runoff depth over flood rise period, mm.

The coefficient of hydrograph asymmetry k_s in the absence of hydrometric observation data on a river is evaluated based on data on a river–analogue.

The coordinates of estimated hydrograph t_i and Q_i are determined by multiplying abscissas x by the duration of flood rise, and ordinates y, by the maximal calculated water discharge ([5], Appendix B, Table B.10) by the formulas

$$t_i = xt_\mathrm{f}, \quad (4)$$

$$Q_i = yQ_P, \quad (5)$$

where $Q_P = q_P A$ is estimated maximal mean daily water discharge of a rain flood, m^3/s (A is drainage area, km^2); t_f is the duration of the rise of rain flood (day), evaluated as

$$t_\mathrm{f} = \frac{0.0116\lambda h_P}{q_P} \quad (6)$$

(q_P is the design modulus of maximal mean daily flood discharge, $m^3/(s\ m^3)$; h_P is the runoff depth with design recurrence, mm).

Thus, to construct a design hydrograph in the absence of hydrometric observational data, one is to determine the maximal mean daily water discharge, the runoff depth of the design recurrence, and the coefficient of flood asymmetry.

ANALYSIS OF HYDROGRAPHS OF RAIN FLOODS

Floods vary widely in terms of the character of their formation and the form of manifestation, largely reflecting the dynamics of the rains that form them. Because of the large number of combinations of the factors that form them, the hydrographs of rain floods are unique.

Single-peak floods are most common in Belarus rivers. The probability of a two-peak flood is on the average ~20%. Three-peak floods are even rarer. Their probability is 10% or less. Many-peak floods (more than three peaks) are extremely rare in the rivers of the country.

The formation of floods with several peaks is due mostly due to the character of precipitation. Two- and three-peak floods formed in Zapadnaya Dvina basin in the autumn of 2009, in many Belarusian rivers in 1998, in the basin of Zapadnyi Bug in the summer of 1988, and in individual years in different rivers of the country. For example, in 1998, when the amount of precipitation was anomalously large, rain floods formed repeatedly in Belarusian rivers and their hydrographs had diverse shapes (Fig. 1).

In small rivers, the flood hydrographs are mostly peaked with abrupt rises and drops. Even a short rain can cause a level rise and often form a small flood wave. In large rivers, maximal levels can keep for several days. In some rivers (Drysa, Nishcha, Yasel'da), the hydrographs are often toothed.

The duration of rain floods depends on many factors (drainage area, rain type, regulation by lakes and bogs, etc.). The mean duration of rain floods in small and medium rivers of Belarus (with drainage area <10 thous. km^2) is ~32 day; it is largest in rivers in the Pripyat basin (~39 days), and equals to ~30 days in the Zapadnaya Dvina basin, ~28 days in the basins of the Neman and Zapadnyi Bug, and ~29 days in the Dnieper basin. In large rivers, the duration of floods is much longer—it averages ~50 days, varying from 45 days in the Zapadnaya Dvina and Neman to 62 days in the Pripyat R., with 50 days in the Dnieper. Floods with shorter duration are caused by short-time rains and storms, while those with longer duration, by steady rains. In the rivers of Poles'e, regulated by lakes and swamps, the duration of summer and autumn floods, which often merge to form one or several large waves, may extend to several months.

Of greatest significance in the construction of flood hydrographs is the duration of rise, which determines the rate of flood formation. The mean duration of flood rise in the Pripyat basin is 16 days, while that for other Belarusian rivers is ~11 days. This characteristics differ considerably for rivers with different drainage areas. In large rivers, water rise can last for 3–4 weeks and even longer.

The duration of flood recession (21 day on the average) is commonly longer than the duration of its rise. It also increases in large (on the average, 26) and decreases in small watersheds (17). Rains are common during flood recession, resulting in the flood hydrographs becoming multipeak. In rivers in the northern and western parts of the country, the duration of water rise is appreciably shorter than that of recession. The shape of flood is more symmetrical in the basins of the Dnieper and Pripyat.

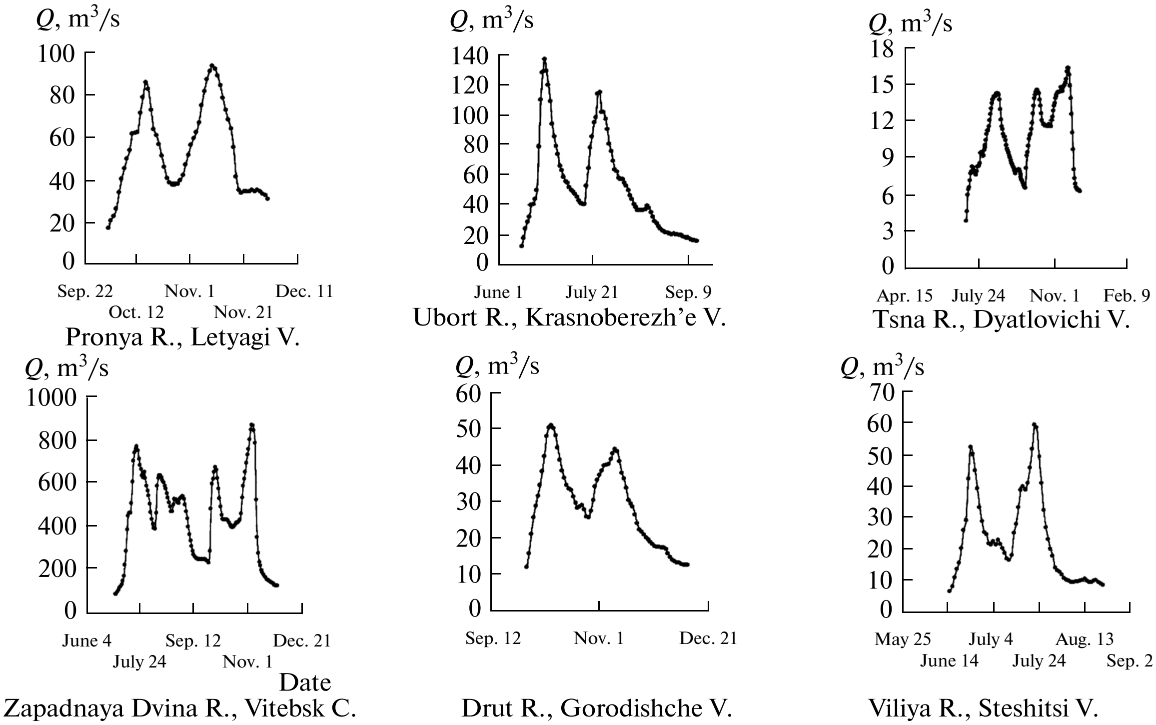

Fig. 1. Rain flood hydrographs for 1998.

TIME DISTRIBUTION OF RAIN FLOODS

The distribution of rain flood over seasons of the year in the period of instrumental observations on rivers in the country was also studied. The floods were divided into three groups in accordance with their formation time: spring (April–early June), summer (June–early September), and autumn (September–November). The boundaries of the seasons may shift depending on the preceding hydrometeorological situation. For example, in the case of a long extended spring flood, precipitation events during its recession may cause rains floods to form against the background of higher spring water and to occur until July. When floods occurred in June after flood recession, they were referred to the summer, while the floods that occurred during higher spring water where referred to the spring. The floods that occurred in September referred to the summer, when their formation started in summer, and to autumn otherwise.

The study showed that the floods that are most common in the country are autumn or summer. The autumn floods mostly dominate in rivers of the Zapadnaya Dvina basin, while the summer flood are most common in the Neman basin. In some Belarusian rivers, the highest rains floods occur in the spring (the rivers of Krivinka, Bobr, and Kopayuvka).

The frequency of floods in different seasons was considered separately for several periods: from the beginning of instrumental observations up to 1965 and from 1965 to 2010. In the period up to 1965, autumn floods dominated in nearly all rivers in the Belarus (50% of rain floods), while summer floods dominated after 1965.

To reveal the effect of current climate changes on the seasonal occurrence of rain floods, period 1965–2010 was divided into two equal periods: 1965–1987 and 1988–2010. The analysis of the number of rain floods over different periods showed that the number of summer floods in the period of current climate warming (1988–2010) was greater than that in the previous period by 10–20%, this difference being the greatest in the Neman basin.

The highest rain floods (with recurrence of <5%) form at a combination of many extreme factors, and their association with some season is weaker. Until 1965, the highest floods were more frequent in autumn, while after 1965, they occurred more often in summer or spring.

THE ROLE OF PRECIPITATION IN THE FORMATION OF RAIN FLOODS

For a flood to form requires some critical amount of precipitation. If the precipitation is less than such amount, no flood will occur in the river. This limit varies with variations in the area and moistening of the watershed, as well as a function of the duration and intensity of precipitation. The initial losses of runoff are due to water losses for filling hollows on watershed surface, infiltration, and evaporation. In the case of dry soils and intense evaporation, water losses are rapid; therefore, even a large amount of precipitation may not cause the formation of rain flood. Observation data show cases to exist, when precipitation at a rate of >80 mm per day did not cause flood, in rivers. Conversely, during a rainy autumn, precipitation of <10 mm transformed into runoff with minimal losses. Thus, the amount of precipitation that causes a flood can depend on several factors. The same amount of precipitation may cause a considerable flood in some cases and no flood in others.

The amount, intensity, and duration of precipitation, as well as its distribution over the drainage area determine the volume of flood runoff and its time distribution, i.e., the shape of hydrograph. Thus, floods caused by heavy rains show high and abrupt rise and recession, while those caused by steady rains are smooth and extended. Floods rarely embrace vast areas. They often extend only to individual river basins.

The formation of floods in rivers is largely governed by watershed areas. In small watersheds, even relatively short rains cause a level rise. The probability that the entire such watershed will be embraced by a shower is much higher than that for a large watershed. In small rivers, the travel time is small, the floods are short, and rain floods rarely overlap. In larger basins, the volume of flood runoff decreases because of retention on floodplain and subsequent evaporation of water. The level rise in a large river is directly dependent on water rise in its tributaries.

Analysis of flood distribution in Belarusian rivers showed no synchronicity in the formation of very high rain floods. Hence, heavy rains and showers are mostly local, not covering the entire area at a time. While the flood in some rivers can be catastrophic, there may be no flood at all in other rivers. However, individual floods were recorded simultaneously in many rivers of the country in 1933, 1962, 1975, 1998, and 2005, though their recurrence varies over the area.

The synoptic situations leading to the formation of floods in rivers are very diverse; the moistening conditions in different seasons preceding the flood are also different. Because of the high variability of soil moisture content over the area, various indirect estimates of the degree of moistening of the basins are widely used. The simplest and most widespread characteristic is the index of preceding moistening, I_w (mm), based on the use of data on precipitation over a long enough preceding period [1]. A simplified formula for calculation has the form:

$$\begin{aligned} I_w &= x_1 + 0.7x_{2-4} + 0.5x_{5-9} \\ &+ 0.3x_{10-14} + 0.2x_{15-30} + 0.1x_{31-60}, \end{aligned} \tag{7}$$

where x_1 is the precipitation amount over the day preceding the estimation day, mm; x_{2-4} is the total precipitation over the period from the fourth to the second day before the estimation day, etc.

Analysis of hydrographs of rain floods with recurrence of ≤25% in rivers with drainage areas up to 10 thousand km^2, situated in different parts of the country, and their formation conditions revealed several typical situations leading to flood formation in rivers. Considered in this case were the total duration of precipitation event leading to flood formation, the precipitation depth of over its formation period, and the index of preceding moistening. The three described situations of flood formation are averaged and rather general.

Spring flood. Rain floods in late winter—early summer form under the conditions when water is still abundant because of spring flood at moisture-saturated soils. In this case, even small amount of precipitation can cause high floods. Water rise caused by rains during flood recession or immediately after its end begins at the first day of precipitation. The index of previous moistening is 45—50 mm. The total amount of precipitation, leading to the formation of spring floods, is generally not large: even daily precipitation of 20—30 m can cause considerable floods in rivers.

Summer floods. Summer floods commonly form as the result of showers at air temperature high enough to keep evaporation elevated; the soil is still able to absorb considerable amount of water. However, notwithstanding the considerable losses, summer floods in Belarus are frequent, because of the predominance of summer precipitation. Rains with daily maximums of >50 mm are more common in July and August (~34 and 26%, respectively) and somewhat rarer in June (~20%). The daily precipitation can be equal to its mean monthly amount or even 1.5—2.0 times greater than that. High summer floods in rivers form because of a series of rains or a long rainy period. The precipitation during a flood can reach 150—200 mm. The index of preceding moistening also varies widely around a mean of 80 mm.

Unlike summer, **autumn floods** show lesser height but longer duration. They form because of frequent steady rains. The predominance of cloudy weather at lower air temperature reduces the evaporation. The index of preceding moistening is ~50 mm. The amount of precipitation required for a flood to form is not very high. Precipitation events are long, though their intensity is low. Autumn floods have lower maximal discharge than spring floods, except for some catastrophic floods, e.g., in 1974.

Thus, the most favorable conditions for flood formation appear after spring snow melting, when soil is moistened up to its field capacity. In summer, soil gets drier through evaporation and transpiration, hence it can intensely absorb water. In autumn, the infiltration capacity decreases again because of the lesser evaporation and the greater precipitation.

The most catastrophic rain floods in rivers in Belarus were recorded in the autumn of 1974 (the basin of the Zapadnyi Bug and the upper reaches of the Pripyat), the spring of 1975 (the Pripyat basin), and 2007 (rivers in Brest oblast).

Table 1. Correlation matrix for maximal unit-area discharges for rain floods with 10% recurrence and hydrographic factors and their logarithmic transformations (bold typed are statistically significant correlation coefficients)

Hydrographic characteristic	Transformation	River basin									
		All Belarusian rivers		Zapadnaya Dvina		Neman		Dnieper		Pripyat and Zapadnyi Bug	
		$M_{10\%}$	$\log M_{10\%}$	$M_{10\%}$	$\log M_{10\%}$	$M_{10\%}$	$\log M_{10\%}$	$M_{10\%}$	$\log M_{10\%}$	$M_{10\%}$	$\log M_{10\%}$
River watershed area A	A	**–0.39**		–0.27		–0.44		**–0.58**		–0.33	
	$\log A$		**–0.62**		–0.46		–0.45		**–0.85**		**–0.69**
Mean watershed elevation, H_m	H_m	0.01		0.10		**0.73**		–0.14		–0.18	
	$\log H_m$		–0.02		0.07		**0.59**		–0.12		–0.23
River length from the source to the observation point L	L	**–0.43**		–0.24		**–0.53**		**–0.62**		–0.38	
	$\log L$		**–0.50**		–0.17		–0.19		**–0.83**		**–0.57**
River network density γ_A	γ_A	0.08		0.12		–0.10		0.05		0.02	
	$\log \gamma_A$		0.12		0.06		0.09		–0.01		0.06
Mean river slope, J_r	J_r	**0.66**		0.48		**0.89**		**0.91**		**0.84**	
	$\log J_r$		**0.71**		0.45		**0.84**		**0.85**		**0.79**
Bog area percentage A_{bog}	A_{bog}	–0.12		–0.03		–0.23		0.04		–0.08	
	$\log(A_{bog}+1)$		–0.18		–0.07		–0.18		–0.08		0.01
Lake area percentage A_l	A_l	–0.17		**–0.70**		–0.38		**–0.69**		–0.35	
	$\log(A_l+1)$		–0.23		**–0.63**		**–0.50**		**–0.69**		**–0.44**
Forest area percentage A_f	A_f	0.13		–0.33		–0.19		0.31		–0.14	
	$\log(A_f+1)$		–0.00		–0.38		–0.19		0.23		–0.10
Gauge latitude, φ	φ	0.09		–0.34		0.41		–0.07		–0.22	
	$\log \varphi$		0.23		–0.36		0.39		–0.05		0.13
Gauge longitude, λ	λ	0.06		–0.12		0.22		–0.15		0.08	
	$\log \lambda$		0.09		–0.08		0.21		–0.08		–0.03

DETERMINATION OF MAXIMAL FLOOD WATER DISCHARGES

To construct rain flood hydrographs requires evaluating maximal water discharges. The method recommended for determining the maximal flood water discharges in the absence of hydrometric observation data on rivers implies the evaluation of some specific characteristics (channel hydraulic parameter; a coefficient accounting for a decrease in maximal water discharge by flow-through lakes, etc.), which may be a difficult task. The authors developed a procedure, which allows the maximal unit-area discharges of rain floods in Belarusian rivers to be evaluated using hydrographic characteristics of watersheds; this procedure gives acceptable results at the stage of preliminary and estimative calculations. The procedure is described in detail elsewhere [3, 4].

For the use of the values of maximal flood water discharges for generalization, they are to be made comparable and converted to the same recurrence. With this in view, *Hydrolog* software complex [2] was used to determine 10%-recurrence maximal water discharges of spring floods, which are represented as unit-area discharges, $m^3/(s\ km^2)$. The choice of such design recurrence is specified by regulatory documents, because the majority of hydroengineering structures are designed for rain flood discharges of 10% recurrence.

The flood-forming hydrographic factors considered in the study included: A, watershed area, km^2; H_m, mean watershed elevation, m; L, river length from its source to the observation site, km; γ_A, river network density, km/km^2; J_r, mean river slope, ‰; A_{sw}, watershed bogginess, %; A_l, lake area percentage on the watershed, ‰; A_f, forest area percentage on the watershed, %. In addition to geographic factors, considered also were geographic coordinates of the centers of gravity of watersheds: φ, the latitude, km, λ, the longitude, km.

Correlation analysis was used to identify statistically significant factors in the formation of maximal unit-area discharges of rain floods with 10% recurrence for Belarusian rivers. As the flood formation conditions vary over the country territory, the analysis of the extent of influence of the factors considered was also carried out within individual large river basins, including the rivers of Zapadnaya Dvina, Neman, Dnieper, Pripyat, and Zapadnyi Bug. To improve the significance of the analyzed factors, correlation analysis was also applied to logarithmically transformed maximal unit-area discharges with 10% recurrence and hydrographic factors. A fragment of the correlation matrix is given in Table 1.

Thus, statistically significant factors for Belarusian rivers as a whole are drainage area, the length of the river from its source to the observation site, and the

Table 2. Models for calculating regional maximal unit-area discharges for rain floods with 10% recurrence in Belarusian rivers

River basin	Model	R
Zapadnaya Dvina	$q_{10\%} = 10^{-3}(8.74J_\mathrm{r} + 0.13L - 2.81A_\mathrm{l} - 0.002A + 28.5)$	0.93
Neman	$q_{10\%} = 10^{-3}(6.63J_\mathrm{r} + 0.0005A - 0.08L - 0.55A_\mathrm{l} + 26.1)$	0.97
Dnieper	$q_{10\%} = 10^{-3}(30.1J_\mathrm{r} + 1.64A_\mathrm{bog} + 0.29H_\mathrm{m} - 7.55A_\mathrm{l} - 48.5)$	0.98
Pripyat and Zapadnyi Bug	$q_{10\%} = \dfrac{10^{3.57}J_\mathrm{r}^{0.38}}{H_\mathrm{m}^{1.94}A^{0.15}(A_\mathrm{l}+1)^{0.43}(\varphi - 50)^{0.72}}$	0.95
All Belarusian rivers	$q_{10\%} = \dfrac{0.057J_\mathrm{r}^{0.37}L^{0.16}}{A^{0.18}}$	0.76

mean river slope. The significance of different factors varies over river basins. For the majority of watersheds, the most significant factor is the mean river slope (apart from Zapadnaya Dvina basin). The role of lake area percentage is high in the basins of the Zapadnaya Dvina and Dnieper, while the mean watershed elevation plays a significant role in the Neman basin.

Regression analysis yielded mathematical models for determining the maximal unit-area discharges for rain floods with 10% recurrence for Belarusian rivers (m^3/(s km^2)). The most effective equations are given in Table 2.

The values of multiple regression coefficient R in the obtained models are high (0.93–0.98), while R values for rivers of Belarus as a whole are somewhat less (0.76). The verification of equations by the comparison calculated and measured values of maximal unit-area discharges with 10% recurrence demonstrated the high efficiency of the proposed equations. Figure 2 correlates the values of $q_{10\%\mathrm{calc}}$ calculated by the formulas and the measured $q_{10\%\mathrm{meas}}$ values of maximal unit-area discharges for rain floods with 10% recurrence in Belarusian rivers.

To determine the maximal unit-area discharge for a flood with another recurrence (P, %), the relationship $q_P = \lambda'_P q_{10\%}$ is used, in which the value of the maximal unit-area runoff with a recurrence of 10% is evaluated from appropriate models (Table 2), where λ'_P is a coefficient for conversion to a unit-area discharge with another recurrence, taken from Table 3.

Thus, the obtained models allow the maximal unit-area discharges with required recurrence to be evaluated as functions of the major hydrographic characteristics of river watersheds.

EVALUATING RUNOFF DEPTH OVER A FLOOD PERIOD

The second problem in the construction of rain flood hydrographs in the absence of hydrometric observations in rivers is the evaluation of rain flood runoff depth with a given recurrence (h_r).

The runoff depth over a flood period h, mm, was evaluated as

$$h = \frac{W}{1000A}, \tag{8}$$

where A is drainage area, km^2; W is runoff volume over the entire flood, m^3, which was determined by summing the mean daily water discharges Q_T from the first day of flood beginning T_b to its end T_e, inclusive:

$$W = 86400\sum_{T_\mathrm{e}}^{T_\mathrm{b}} Q_T. \tag{9}$$

To eliminate the component of groundwater recharge in the formation of rain flood, water discharges corresponding to the dates of flood beginning T_b and end T_e were added to the sum with factors 1/2.

The obtained runoff depths for flood period were ranked. Three-parameter gamma distribution was used to evaluate the runoff depths during floods with 1, 5, 10, and 25% recurrence.

Runoff depths over a flood with 10% recurrence were mapped using the coordinates of the centers of gravity of river watersheds under considerations (Fig. 3). To determined the runoff depths for floods with another recurrence, coefficients λ''_P were obtained (Table 4).

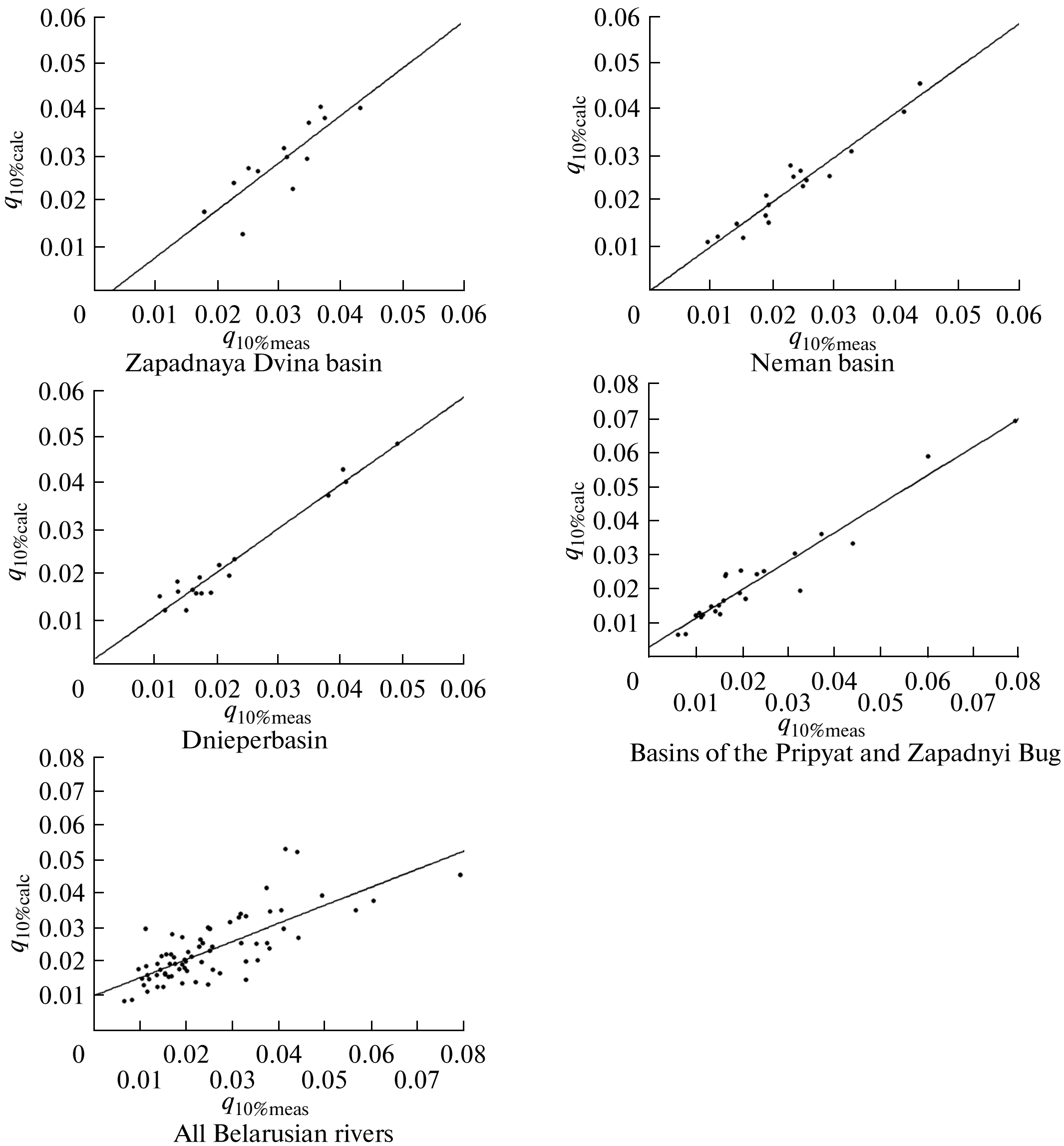

Fig. 2. Correlation of calculated and measured values of maximal unit-area flood discharges.

Thus, the estimated depth of rain flood runoff (h_P) with the required recurrence (P, %) was evaluated by the relationship $h_P = \lambda''_P h_{10\%}$, in which the runoff depth for a flood with recurrence of 10% ($h_{10\%}$) is determined from the map (Fig. 3), λ''_P is a conversion factor for a runoff depth with another recurrence, taken from Table 4.

Analysis of the map shows that the largest values of runoff depth over the flood are typical of rivers in the northern part of Belarus—on the average 45–50 mm, while somewhat lesser values are recorded in the extreme south. The values of runoff depth are the least in rivers in the east and extreme southwest of the country—25–30 mm. In other rivers of the country, the mean runoff depth over a flood is 35–40 mm.

The parameters for the maximal water discharges for floods and the respective runoff depths are not equal, a coefficient μ was introduced in the formula (6) for flood rise duration; the values of this coefficient are determined by Table 5. Now, formula (6) becomes:

$$t_{\mathrm{f}} = \frac{0.0116\lambda h_P \mu_{10\%}}{q_{\mathrm{d}}}, \quad (10)$$

where $\mu_{10\%}$ is a factor accounting for the unequal statistical parameters of the runoff depth over a flood and maximal water discharges.

Thus, a map was constructed for determining the depth of rain flood runoff with 10% recurrence, which can be used to evaluate the runoff depth over a flood without involvement of rivers–analogs, and coeffi-

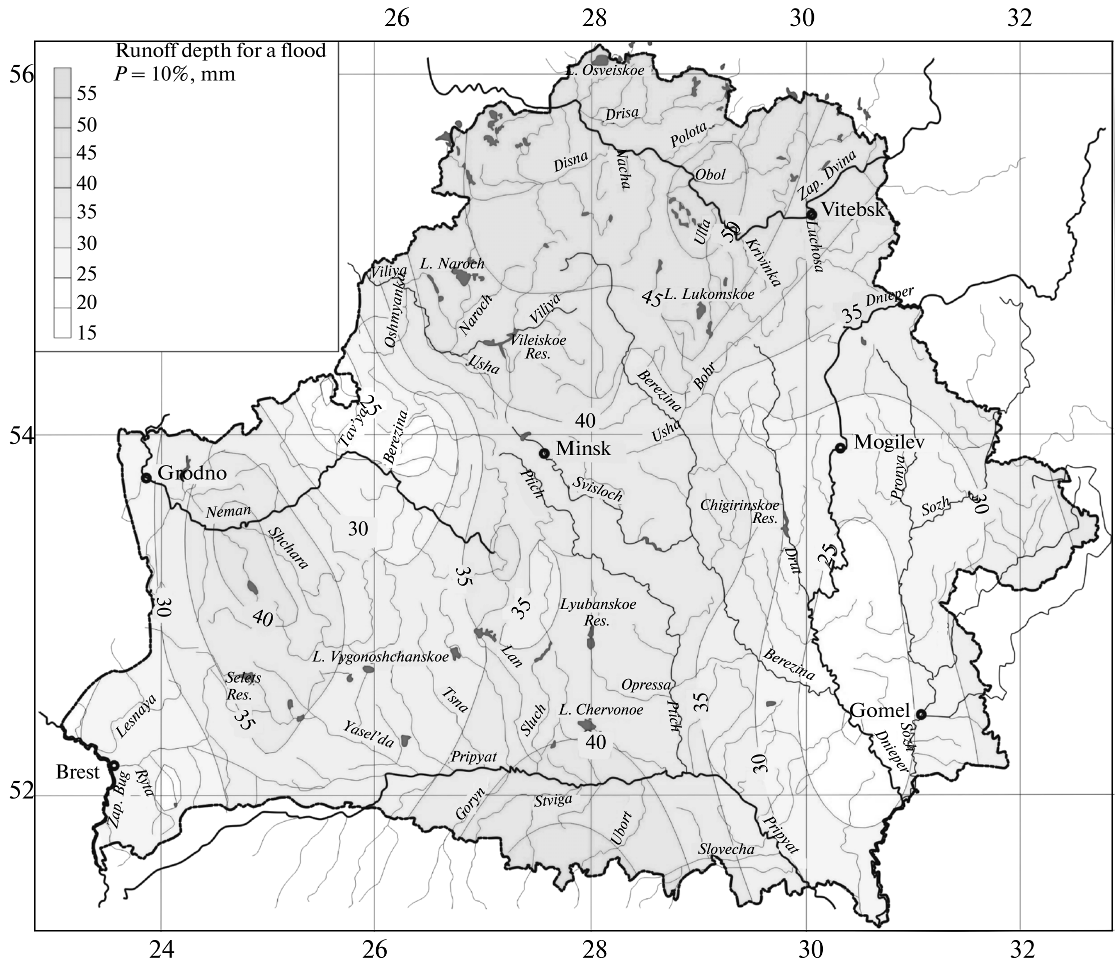

Fig. 3. Runoff depth with 10% recurrence in Belarusian rivers.

cients for conversion from 10% to other design recurrences were calculated.

COEFFICIENTS OF ASYMMETRY OF FLOOD SHAPE

The third problem in the construction of rain flood hydrographs is the calculation of hydrograph shape coefficient λ, which is determined depending on the asymmetry coefficient k_s.

In [5], it is recommended to take asymmetry coefficients from rivers–analogs; in case there is no such rivers, it is admissible to assume $k_s = 0.30$. However, because of the difference between the formation conditions and the specific features of rain flood passage in different rivers in Belarus, as well as to improve the

Table 3. Conversion coefficients λ'_P of maximal unit-area discharges of rain floods from 10% to other recurrences

River basin	1%	5%	10%	20%	25%
Zapadnaya Dvina	1.88	1.35	1	0.66	0.60
Neman	2.04	1.30	1	0.76	0.70
Dnieper	2.74	1.52	1	0.74	0.65
Pripyat and Zapadnyi Bug	2.10	1.33	1	0.69	0.60
All Belarusian rivers	2.16	1.39	1	0.72	0.65

Table 4. Conversion coefficients λ''_P for unit-area discharges for rain floods from 10% to other recurrences

P, %				
1	5	10	20	25
2.03	1.28	1	0.71	0.65

accuracy of calculations, mean coefficients of asymmetry were calculated for rain flood hydrographs for rivers given in Table 6.

The values of asymmetry coefficients given in Table 6 ([5], appendix B, Table B.10) are used to determine the coordinates of design hydrograph.

CONSTRUCTION OF RAIN FLOOD HYDROGRAPHS

The construction of rain flood hydrograph in the absence of hydrometric observation data follows the algorithm:

(1) a map is used to determine the position of the river under consideration and its drainage basin for the outlet section, as well as hydrographic characteristics;

(2) the maximal unit-area discharge for a rain flood with 10% recurrence is calculated with the use of hydrographic characteristics of the drainage basin;

(3) the passage is made to a maximal unit-area discharge for the required design recurrence with the use of coefficient λ'_P (Table 3);

(4) runoff depth is evaluated for a flood with 10% recurrence using a map (Fig. 3);

(5) conversion is made from a runoff depth of 10% recurrence to runoff depth with a required design recurrence with the use of coefficient λ''_P (Table 4);

(6) the coefficient of asymmetry of rain flood k_s is calculated (Table 6);

(7) depending on the coefficient of asymmetry of hydrograph k_s, the relative abscissas x and ordinates y of the design hydrographs according to [5];

(8) the coefficient μ is evaluated to account for the inequality of runoff depth parameters and the maximal discharge of rain floods (Table 5);

(9) the duration of rain flood rise t_f is evaluated from (10) and the maximal mean daily water discharge of the rain flood Q is calculated;

(10) formulas (4) and (5) are used to calculate the abscissas and ordinates of the design hydrographs;

(11) the obtained values are used to construct rain flood hydrograph.

The comparison of rain flood hydrographs, constructed using the proposed procedure, showed them to be in satisfactory agreement.

CONCLUSIONS

The mean duration of rain floods in small and medium rivers of Belarus is ~32 days, and in large rivers is ~50 days. The duration is longest in the Pripyat basin and shortest in the basins of the Neman and Zapadnyi Bug.

The conditions for the formation of rain floods are most favorable after spring snow melting. In summer, when soil can intensely absorb water, the amount of precipitation, leading to flood formation, can reach 150–200 mm. In autumn, floods form because of frequent steady rains against the condition of lower evaporation. Autumn and summer floods are more common in Belarusian rivers. However, while autumn floods dominated in nearly all rivers for the country before 1965, summer floods became more frequent after 1965.

The study improved the existing procedure for constructing rain flood hydrographs in Belarusian rivers in the absence of hydrometric observation data in rivers without the use of rivers–analogs. Some calculations

Table 5. Values of coefficient μ, accounting for the inequality of runoff depth parameters and maximal water discharges during rain floods

River basin	*P*, %				
	1	5	10	20	25
Zapadnaya Dvina, Neman, Zapadnyi Bug	1.0	0.98	0.95	0.89	0.86
Dnieper and Pripyat	1.0	0.97	0.94	0.87	0.83

Table 6. Coefficients of asymmetry of rain flood hydrographs for Belarusian rivers

River basin	Value of coefficient k_s
Zapadnaya Dvina, Neman	0.29
Dnieper, left tributaries of the Pripyat, Zapadnyi Bug	0.31
Right tributaries of the Pripyat	0.33

were improve and simplified; the estimation of the characteristics of flood runoff was made more reliable; most recent data of hydrometric observations of floods were used. To determine the maximal unit-area discharges, regional mathematical models were developed, allowing maximal unit-area discharges for floods to be determined with the use of hydrographic characteristics of watersheds. A map was constructed for evaluating runoff depth during flood with 10% recurrence. Coefficients for conversion to other design recurrences were calculated. A table of coefficients of flood shape asymmetry was proposed, as required for determining the abscissa and ordinate of the design hydrograph, as well as the coefficient of hydrograph shape. The proposed procedure yields results acceptable for practice and can be used to solve scientific and practical problems.

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