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Small Urban River Runoff Response to 2020 and 2021 Extreme Rainfalls on the Territory of Moscow

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Abstract—An important trend of modern development is the concentration of population in urban agglomerations, where a specific meso- and micro-climate is created under conditions of dramatically transformed natural landscapes. In the present paper, the long-term statistical analysis of intense rainfalls and annual daily precipitation maxima was carried out based on the Moscow region weather stations timeseries for the period of 1966–2021. An increase in the variability of intense precipitation over the Moscow region corresponding to the formation of significant floods was revealed in some years. The COSMO-CLM model simulated extreme precipitation for the basin of the Setun' River (190 km^2), the largest right-bank tributary of the Moskva River within the Moscow city, which was recorded over Moscow in May 2020 and June 2021. Maximum precipitation was registered over the Setun' River basin during 45–90 minutes and induced rainfall floods that exceeded the spring flood by two times. The estimated basin travel time was 6–8 hours. Rainfalls form a multistep hydrograph inheriting the shower precipitation structure on small rivers.

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INTRODUCTION

Studying extreme precipitation, which includes heavy and very heavy showers according to the classification of Hydrometcenter of Russia [7], is one of the major directions of urban climate research [19]. In the recent 20 years, the structure of precipitation in urban agglomerations has significantly changed toward an increase in the intensity of short-term showers. For example, a significant increase in extreme hourly precipitation was observed in Shanghai during the 20th century, its frequency has particularly increased during the period of intense urbanization since 1981 [17]. The studies of the precipitation regime in European cities also revealed the increasing intensity of short-term precipitation [13]. This fact, as well as the transformation of the catchment resulting in a decreasing travel time and duration of floods, the organization of storm sewage collectors lead to an increase in peak discharges on the urban rivers [23]. Road embankments play a role of local watersheds and, together with terrain [11, 16], form a reverse effect associated with an increasing travel time. The observed changes are complemented with an artificial water regime transformation related to the snow removal from urbanized areas and the snowmelt during the period of winter low water.

In 2020 and 2021, rainfalls characterized by extreme intensities were observed in Moscow in summer. The most significant events were registered on May 29–30, 2020 [1], when 140% of the monthly normal was recorded during two days, and on June 28–29, 2021 [5]. In the absence of the rainwater control system and under conditions of the dense building of Moscow, the rainfalls led to the flooding of coastal areas, especially in the park zones adjacent to small watercourses [9]. The activation of erosion phenomena and the increased sediment runoff were registered. Since municipal and federal environmental services do not provide the hydrological monitoring of small rivers within Moscow, there are no estimates of water runoff for such events. This complicates the forecast of such rainfall manifestations and the scientific substantiation of the systems for their prevention. At the same time, the automated measurements of water runoff at the station network with a resolution of 30 minutes have been carried out during the mentioned flood events in the basin of the Setun’ River, the right-bank tributary of the Moskva River, where the system for the hydrological and geochemical monitoring implemented by the Moscow State University (MSU) Faculty of Geography has operated since 2019 [24, 25]. Together with the MSU Meteorological Observatory, which is located within the basin of this river and provides the most complete observations of the rainfall structure at the station recording rain gage, this territory is optimal for studying extreme rainfalls in 2020 and 2021. The objectives of the present paper are to generalize long-term data on extreme precipitation during 1966–2021 at the Moscow region weather stations to characterize the extremity of the 2020 and 2021 events, to simulate rainfalls on May 29–30, 2020 and June 28–29, 2021 with the COSMO-CLM model, and to provide the statistical analysis of the response of the Setun’ River water discharge to the precipitation regime.

METHODS

The series of daily and hourly precipitation from the archive of All-Russian Research Institute of Hydrometeorological Information–World Data Center (ARIHMI–WDC) [4] for MSU Observatory, Losinoostrovskaya, im. Nebol’sina, Krylatskoe, Tushino, im. Mikhel’sona, Egor’evsk, Podmoskovnaya, Nemchinovka, VDNKh, and Balchug stations for the period from 1966 to 2021 were used as initial data to obtain the statistical characteristics of the precipitation regime. Gaps in the daily series were filled with archival data of Roshydromet Administrations for Hydrometeorology and Environmental Monitoring or PogodaiKlimat website [8]. The most complete data series were collected for MSU, Balchug, Nemchinovka, Podmoskovnaya, Tushino, and VDNKh stations. A variation in the frequency of extreme precipitation was analyzed over the observation period. The trends were estimated based on the ETCDDI indices [15, 21]: *Rx1day* is monthly maximum 1-day precipitation; *R10mm* is the annual count of days when precipitation was 10 mm; *R20mm* is the annual count of days when precipitation was 20 mm; *R30mm* is the annual count of days when precipitation was 30 mm; *PRCPTOT* is annual total precipitation on the days with precipitation >1 mm; *R95pTOT* is annual total precipitation on the days with precipitation >95th percentile; *R99pTOT* is annual total precipitation on the days with precipitation >99th percentile.

The assessment of the regime of extreme rainfalls and the response of runoff to them was carried out for the model basin of the Setun’ River (Fig. 1), within which two of the aforementioned stations are situated: MSU and Nemchinovka, they were used as reference ones in the present study. The Setun’ River is the largest right-bank tributary of the Moskva River within the Moscow city and all upper and middle reaches. The length of the river is 38 km, the catchment area is 190 km^2. The modeling of extreme precipitation for this territory was based on the COSMO-CLM v5.12 nonhydrostatic model [22]. The standard scheme of nested grid was used. The following data were used as initial and boundary conditions: the ERA5 global reanalysis data with a horizontal resolution of 0.25 (~30 km) [14] were used for the base model domain, and model outputs of the base model domain with a decrease in the horizontal resolution and modeling area were used for the nested grid. The base model domain with a resolution of 0.027 (~3 km) covered most of the European part of Russia and has 500 grid points in both horizontal directions. The nested model domain with a resolution of 0.009 (~1 km) fully focused on the Moscow region. The model was run with a time step of 40 s for the base domain and 10 s for the nested grid. Based on the information about the external parameters of the Earth’s surface within the model domains with a corresponding resolution for each model cell [26], the TERRA-URB module for the urban canopy parameterization was used [26–28].

Two test experiments were held for the periods of May 28–June 2, 2020 and June 27–July 3, 2021. Model outputs were generated every 15 minutes, the information on total precipitation for every 15 minutes during the whole observation period was obtained. The timeseries for the grid points with a step of 1 km situated within the Setun’ River model basin were analyzed separately (in total, 190 points) and with account of the division of the Setun’ River into subbasins (Fig. 1). To verify the model data, the comparison with observations was carried out for the nearest points to the main Moscow region weather stations. The comparison was performed for 3–6-hour (only for the 2020 experiment due to the absence of the station data for the 2021 experimental period) and daily precipitation.

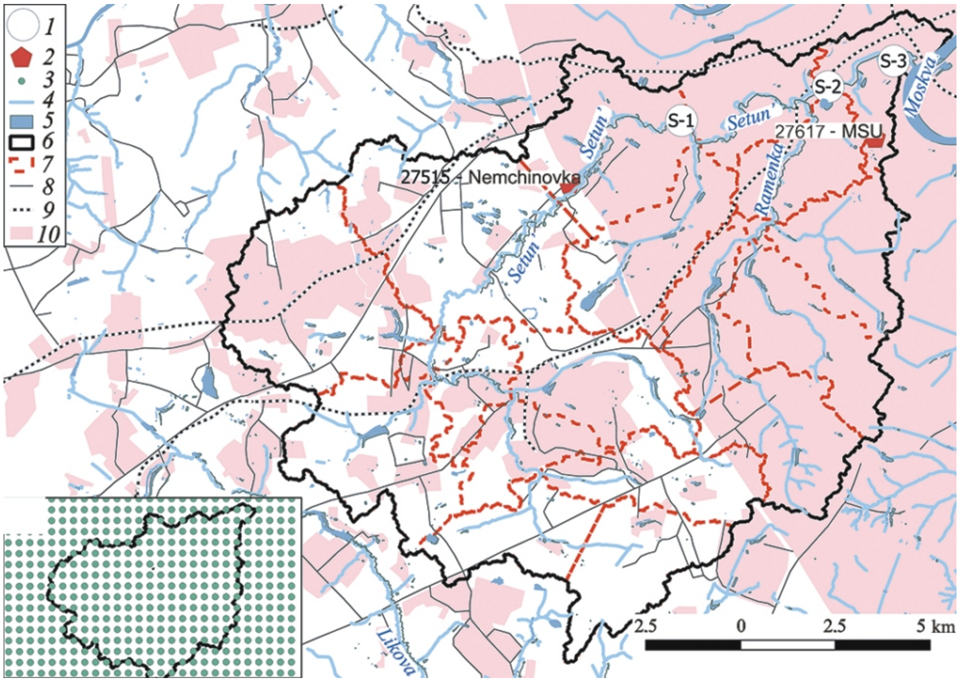

Fig. 1. The map of the Setun' River subbasins with indication of the COSMO-CLM model grid points with a grid spacing of ~1 km (the inset) and hydrological monitoring stations in 2019–2021 used in the present study: (*1*) gaging stations; (*2*) weather stations; (*3*) COSMO grid; (*4*) rivers; (*5*) lakes; (*6*) catchment border; (*7*) subcatchment borders; (*8*) motor roads; (*9*) railroads; (*10*) settlements.

Based on the data from the recording rain gage at the MSU Observatory station, rainfall reduction curves were constructed for 1997–2020. The samples of the annual maximum precipitation intensities per 10, 20, 40, 60, 90, 150, 300, 720, and 1440 minutes were obtained, the distribution laws were determined using the Pearson type III probability curves. The calculated quantiles of 1, 2, 5, 10, 20, 25, 30, 40, and 50% were determined for subsequent calculations. The rainfall reduction curves were constructed by dividing total precipitation with a specified duration and probability by the daily maximum with the same probability. The resulting ordinates were compared to the values of the rainfall reduction curve according to SNiP 2.01.14-83 [10].

Data of automated water level observations at three stations (S-1, S-2, S-3) located in the middle and lower Setun' River area were used to study water runoff (Fig. 1). The measurements have been continuously carried out using the HOBO U20L and Solinst Levelogger 5 Junior loggers with a recording time step of 30 minutes since November 14, 2019. The principle of water level measurements with a hydrostatic level gage is based on the dependence of hydrostatic pressure on the height of a water column over a pressure sensor [6]. The loggers were installed in the river channel and were fixed at a level below low-water ones. Data reading from the loggers was carried out in field conditions using an optical data exchange system several times per year. The construction of the calculation relationship of water level and discharges for the monitoring gages was based on the Chezy formula with the calculation of roughness coefficients based on the water discharge measurements for channel sectors and based on the reconnaissance hydromorphometric survey for floodplain sectors. The analytic expression for the dependence of water discharge and water levels for the stations was schematized by the analytic functions that are applicable only until the middle and high overflow. For example, for station S-3 in the calculated height range of 122.6–124.9 m BS, the relationship between the water discharge Q and water level H can be expressed as follows:

$$Q \quad 1.33(H \quad 122.5)^3 \quad 1.73(H \quad 122.5)^2 \quad 0.53(H \quad 122.5) \quad 0.12.$$

The relationships are updated in the process of accumulation of data on the measured discharges and do not take into account possible changes related to the disturbance of the flow hydraulics caused by local retaining effects (riverbed deformations, wood debris, etc.).

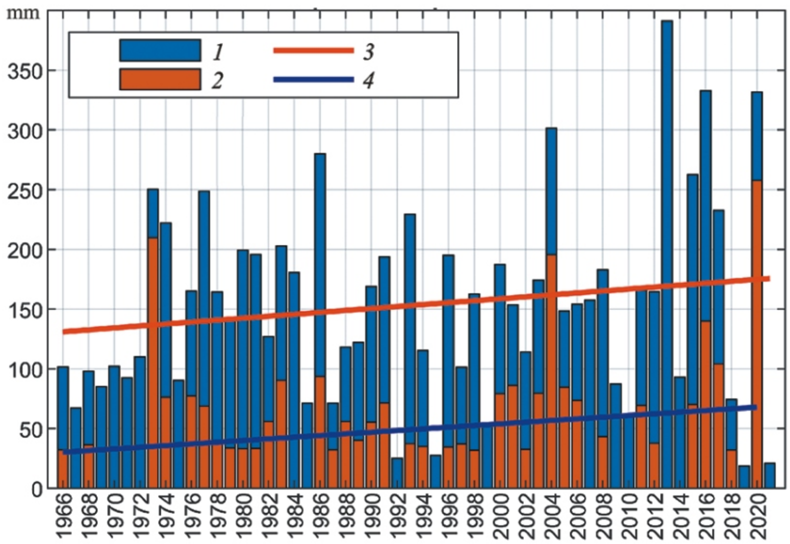

Fig. 2. The long-term series of (*1*) *R95pTOT* and (*2*) *R99pTOT* indices at MSU weather station and their trend lines, respectively: (*3*) $y = 0.81x - 1467.2$; (*4*) $y = 0.70x - 1344.4$.

Hydrological data were generalized for a single station located within the Setun' River basin, namely, Zavod "Slozhnye Efiry" stream gage, where daily measurements of water discharge were carried out during 1979–1988 (except 1982 and 1986). For all mentioned series of water runoff, the response to precipitation falling to the catchment was evaluated. The Pearson correlation coefficient *R* and Shannon mutual information coefficient *MI* [12, 20] were used. The latter shows how much entropy (uncertainty) of a random variable (in this case, the water discharge of the Setun' River) can be reduced using another random variable (total precipitation at weather stations). It is a convenient tool for estimating nonlinear connections without mathematical models [18, 29]. The correlation coefficients (*R*) and mutual information (*MI*) were determined between the average daily discharges and the following variables: total precipitation for a current day; total precipitation for the day 2, 3, 4, 5, 6, and 7 days ago (for yesterday, the day before yesterday, etc.); total precipitation for 2, 5, 7, and 14 previous days.

DISCUSSION AND RESULTS

In the recent years, there has been an increase in extreme daily precipitation within the Moscow region. Until 2000–2002, the annual daily precipitation maximum remained within 50–60 mm. In the subsequent years, the frequency of the maxima above 70 mm increased (4–5 years at several stations). The coefficients of linear trends of the absolute annual maxima of daily precipitation are positive at all stations, but are almost everywhere insignificant at the level of 5 and 15%. The exception is Nemchinovka ($p_{\text{value}} = 0.0295$) and Podmoskovnaya ($p_{\text{value}} = 0.1437$) stations. In the recent decades, there has been an increase in the intensity of short-term (tens of minutes and hours) rainfalls [2]. For MSU (Fig. 2) and Nemchinovka stations located within the Setun' River model basin, the indices *R95pTOT* and *R99pTOT* show annual precipitation for the days when daily precipitation was above the long-term 95% and 99% percentiles for a given station. The trends in *R95pTOT* at both stations are similar with the aforementioned annual maxima: do not exceed 300 mm before 2010, reach 400 mm and more in 2013, and are close to the value of 300 mm or exceed it in 2–3 cases after that. For *R99pTOT*, MSU station is characterized by the higher variability and the greater number of extreme outliers (1973, 2004, and 2020), and these values are higher than at Nemchinovka station (200–250 mm and <200 mm, respectively). At the same time, the variation in *R99pTOT* is smoother at Nemchinovka. The trends in both variables at both stations are positive, but only *R95pTOT* at Nemchinovka (at the 5% level) and *R99pTOT* at MSU are significant (at the 5% and 15% level, respectively). The index *R10mm* reaches 30–35 days per year (the maximum is higher in Nemchinovka), its noticeable growth during the available period has been registered only at Nemchinovka since the late 1990s. At MSU station, the distribution of values is more homogeneous for these years. For *R20mm*, the frequency of high values (>5 days) has noticeably increased since the second half of the 2000s

Table 1. Daily total precipitation, the probability and number of days with the same total precipitation per 100 years at the Moscow region stations for the periods of May 27–29, 2020 and June 27–29, 2021

Station	2020									2021					
	May 29			May 30			May 31			June 27–28			June 28–29		
	P		*n*	*P*		*n*	*P*		*n*	*P*		*n*	*P*		*n*
Balchug	32	99.75	89	20	98.91	397	33	99.79	75	19	98.75	456	0	50.70	17982
MSU	38.7	99.86	51	31.7	99.68	114	32.5	99.71	103	–	–	–	–	–	–
Nemchinovka	23	99.28	218	36	99.77	68	32	99.69	93	22	99.24	233	0.8	67.76	9870
Podmoskovnaya	52	99.98	5.37	34.3	99.78	68	41	99.91	27	11	96.67	1042	0.6	65.18	10885
Tushino	41.5	99.90	35	26.4	99.50	180	34	99.77	83	33	99.73	97	37	99.83	59
VDNKh	38	99.82	64	23	99.23	277	34	99.76	86	20	98.93	388	0.4	59.42	14739

P is total precipitation, mm; is percentile, %; *n* is the number of days per 100 years.

(4–5 years with the values of 5 day and more). Due to the higher rareness of values (2–3 days per year), the values of *R30mm* do not exhibit a noticeable trend over the available observation period, and the year 2020 is especially pronounced (6 days). The trends are positive everywhere except *R10mm* at MSU station (negative but insignificant). The trends in *R10mm*, *R20mm* turned out to be significant at the 5% level at Nemchinovka station, and no significant trends were found for MSU station. This is generally consistent with the data from [3] about a significant increase in annual precipitation at Nemchinovka station and a maximum increase in the number of cases with precipitation above 10, 15, and 20 mm here. The ordinates of rainfall reduction curves demonstrating the value of the precipitation layer over a specified time interval in fractions of the daily precipitation maximum (for the same probability) for time intervals below 300 minutes increased approximately by 20–25%.

The calculations of the statistical significance of the series of the absolute daily maxima, parameters *R95pTOT*, *R99pTOT*, *R10mm*, *R20mm*, *R30mm* for MSU and Nemchinovka stations using the *t*-test for mean values and *F*-test for standard deviations for the halved samples (1966–1993 and 1994–2021) demonstrated significant differences in variance, especially for the parameters of medium extremity (*R20mm*, *R95pTOT*). The *t*-test revealed a significant difference in the means at the 5% level only for *R95pTOT* in Nemchinovka ($p_{\text{value}} = 0.04$), at the 10% level for *R10mm* in Nemchinovka ($p_{\text{value}} = 0.08$). In addition, p_{value} was ~0.16 for the absolute daily maxima in Nemchinovka. For the other parameters, p_{value} was much higher. The *F*-test demonstrated more significant differences between the analyzed periods in terms of the variability of parameters. For example, differences in variances turned out to be significant at the 5% level for *R10mm* and *R20mm* in Nemchinovka, *R20mm* and *R95pTOT* at MSU and at the 10% level for *R95pTOT* in Nemchinovka and absolute daily maxima for MSU. The same differences in the variance of some parameters were also significant at the 15% level.

The test experiments with the COSMO-CLM for the Setun' River model basin successfully reproduced precipitation during May 28–June 2, 2020 and June 27–July 3, 2021. Precipitation on May 29, 2020 at some stations reached 52 mm, which corresponds to the frequency *n* from 35 to 218 days per 100 years; precipitation on June 28, 2021 reached 33 mm (*n* = 233 days per 100 years) (see Table 1). The situation on May 29, 2020 according to model data was characterized by the movement of the extensive precipitation zone from southeast to northwest through the Setun' River basin within the time interval of 22:15–23:00 UTC, the first rainfall maximum (up to 7–8 mm/15 minutes) was associated with it. The rainfall maximum crossed the Setun' River basin from south to north for 1–1.5 hours. The second precipitation maximum was simulated during 02:00–03:15 UTC on May 31, 2020, reached smaller values (2–3 mm/15 minutes) and affected the smaller number of subbasins (in the east and southwest). Precipitation on July 28, 2021 was shorter but more intensive. The precipitation zone in the model domain was smaller and passed through the Setun' River basin from south to north during 30–45 minutes (14:45–15:30 UTC), the maximum intensities reached 25 mm/15 minutes and mainly affected western subbasins.

The multistage hydrograph was formed during the period of extreme rainfalls in the summer of 2020 and 2021 on the small rivers of Moscow. The maximum water discharge in the Setun' River on May 29–31, 2020

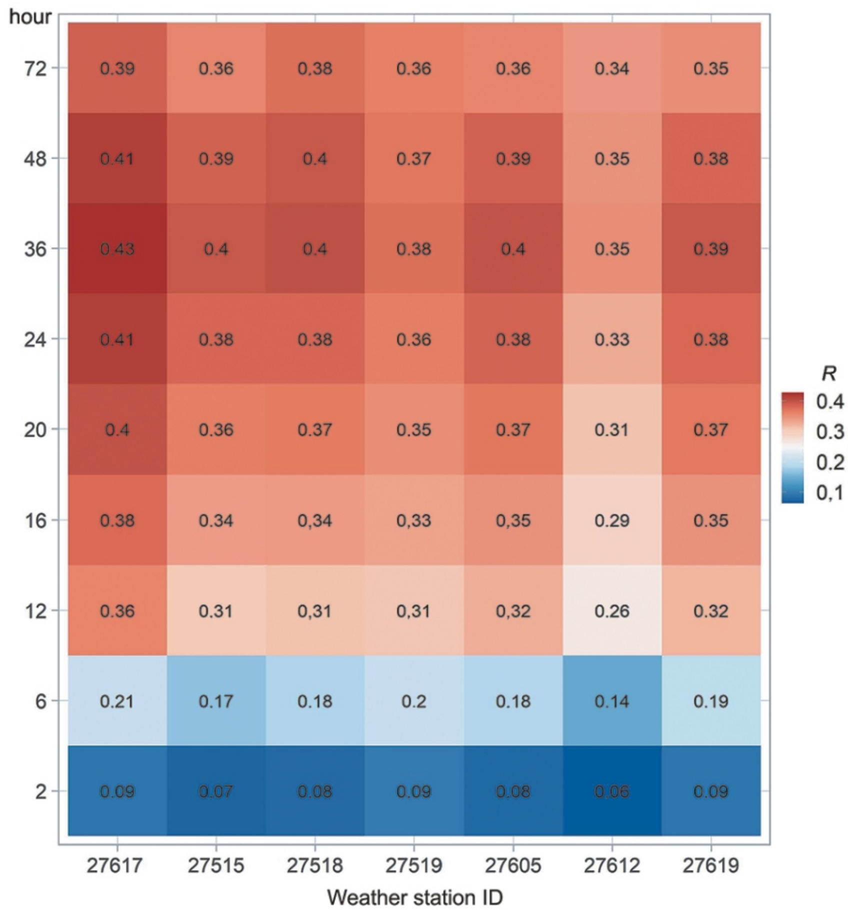

Fig. 3. The coefficient of correlation between the Setun' River water discharge (station S-3) according to measurements in 2019–2021 and total precipitation over the period from 2 to 72 hours (2019–2021) for the weather stations: MSU Observatory (27617), Nemchinovka (27515), Podmoskovnaya (27518), im. Mikhel'sona (27519), Balchug (27605), VDNKh (27612), Tushino (27619).

was much above the flood peak. Its estimated probability was within 4–7%. The flood started in the process of showers at 06:00 UTC on May 29, 2020. Its first peak fell on 11:30 on May 29, 2020 (16 m^3/s). Then, after the short-term decline of water discharge, the main flood wave was formed, its peak was registered at 04:00 UTC on May 30, 2020 (32 m^3/s). The two-fold increase in the runoff of the second wave was associated with the saturation of soil and a high degree of the hydrographic network filling. Due to this effect, increased water levels were recorded until June 7. At night on May 30, the middle and even high overflow was registered for most of unregulated rivers of Moscow and the Moscow region, which was accompanied by significant damage to neighboring infrastructure. Showers on June 28, 2021 formed a rainfall flood in the Setun' River catchment that exceeded the spring flood by two times. During the preceding 10 days, there were low-water discharges of about 5 m^3/s at the outlet. In the daytime on June 28, the discharge grew by three times per hour (from 13:00 to 14:00 UTC) and exceeded 24 m^3/s in the evening. The flood recession lasted three days and, by July 1, water discharges at the outlet returned to the low-water values.

The analysis of the coefficients of correlation between hourly rainfall and water discharges demonstrated (Fig. 3) that the highest significant correlations were found for the previous precipitation registered 6–8 hours ago at MSU weather station ($R = 0.14$, the significance level = 0.05, the number of cases $N = 16054$). At the same time, almost the same high values ($R = 0.13$) were typical of Nemchinovka, Podmoskovnaya, Balchug, and VDNKh stations. All mentioned stations are within the Setun' River catchment or are quite close to it (<10 km). The value of the correlation coefficient cannot imply significant correlation but indicates the presence of a steady signal from precipitation in the series of water discharge observations. The values of the coefficient of correlation between the water discharge and preceding precipitation allow determining the characteristic basin travel time for the Setun’ River basin at a level of 6–8 hours. Such short travel time of liquid precipitation may be explained by the presence of the great number of impermeable (asphalt, concrete, etc.) surfaces in the basin, which do not allow precipitation to soak into the soil and provide its fast inflow to the river network.

Total precipitation accumulated over the period from 2 to 72 hours exhibit significant correlations with runoff. The highest values are typical of 36-hour total precipitation at MSU weather station ($R = 0.43$, $= 0.05$, $N = 16054$). At the same time, R 0.4 for total 20- to 48-hour precipitation and starts decreasing only by 72 hours. A similar comparison of average daily water discharges of the Setun’ River at Zavod “Slozhnye Efiry” station and total precipitation for a current day for 1979–1988 showed that the maximum correlation coefficients were found for total precipitation for 3 and 4 days according to Kuntsevo weather station ($R = 0.14$, $= 0.05$, $N = 2525$) and total precipitation for two days ago also for Kuntsevo station ($R = 0.13$, $= 0.05$, $N = 2525$). The Shannon mutual information *MI* for reducing entropy of daily water discharges of the Setun’ River does not exceed 0.5 bit and is also quite high for Kuntsevo station: 0.36–0.37 bit for total precipitation for 1–2 days and 0.4 for daily precipitation for three days ago. The maximum mutual information was found for daily precipitation for three days ago (0.51 bit) and total precipitation for 1 day (0.46 bit) at Tushino weather station.

CONCLUSIONS

The present study for the first time investigated features of the long-term variability of extreme precipitation on the territory of Moscow and estimated the response of water runoff of small rivers (the Setun’ River) to it. The following conclusions were made.

An increase in the absolute annual daily maximum rainfall and an essential growth of the parameters of the mean extremity of precipitation (*R95pTOT*, *R20mm*) are observed in the Moscow region. The estimated displacement of rainfall reduction curves according to MSU Meteorological Observatory observations using a recording rain gage over the period from 1997 to 2020 is 20–25%, which corresponds to an increase in the precipitation intensity by 10–15%.

Against this background, maximum precipitation was recorded in 2020 and 2021. Precipitation on May 29, 2020 reached the frequency of 35 days per 100 years, and precipitation on June 28, 2021 reached the frequency of 233 days per 100 years. The passage of maximum precipitation through the Setun’ River basin lasted 1–1.5 hours on May 30, 2020 and about 45 minutes on July 28, 2021.

Showers form the multistage hydrograph inheriting the precipitation structure on small rivers. The estimated characteristic basin travel time during the period of showers for the Setun’ River basin is 6–8 hours. Maximum values of runoff correspond to 36-hour total precipitation. The successful prediction of extreme floods in the Setun’ River basin requires an accurate meteorological forecast for MSU, Tushino, and Kuntsevo weather stations with a lead time of 1 to 3 days.

An important methodological result of the present study is the simulation of extreme rainfalls during the 2020 and 2021 experiments with the latest version of the COSMO-CLM model. Model errors in determining the duration of precipitation and some cases of light precipitation require more detailed analysis of synoptic conditions and the spatial distribution of precipitation using archival weather radar data. It also requires spatial verification methods due to the fact that the model could reproduce maximum precipitation zones with a certain displacement relative to the stations. The use of pluviogram data for MSU station for corresponding periods, as well as the hydrological model of water and chemical runoff will allow developing an integrated system for the prediction of extreme precipitation and runoff for small river catchments of Moscow in the nearest future.

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