REPUBLIC OF AZERBAIJAN

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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

ANALYSIS OF SPATIAL AND TEMPORAL PATTERNS OF HEAVY RAINFALL INTENSITY IN THE TERRITORY OF AZERBAIJAN

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Field of science:	Geography
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GENERAL CHARACTERISTICS OF THE STUDY

Relevance of the topic and state of research. Short-duration but intense rainfall increases surface erosion, hampers economic activities, and adversely affects pollination conditions during plant flowering. In mountainous areas, debris flows and floods sometimes destroy bridges and damage settlements, buildings, agricultural land, and private property along rivers. Moreover, impermeable surfaces in urban areas generate large volumes of surface runoff, creating difficulties for stormwater drainage.

New roads and railways are currently being constructed in Azerbaijan, together with bridges, water-supply facilities, and wastewater and stormwater drainage systems. Solar and wind power plants are also being developed in arid areas exposed to flood risk, while agricultural land is expanding. These projects require estimates of peak river discharge, including for small flood-prone rivers and ephemeral watercourses. The action plan for the reintegration of the Karabakh and East Zangezur economic regions likewise envisages such projects. Reliable design, construction, and sustainable operation of these infrastructure facilities require data on maximum daily precipitation and their regional generalization. This makes the investigation of spatiotemporal rainfall patterns relevant and increases the significance of the dissertation.

Compared with annual precipitation, methods for investigating extreme precipitation are less developed. The formation conditions, quantitative characteristics, and spatial and temporal variability of heavy rainfall in Azerbaijan have been insufficiently studied. However, the spatiotemporal patterns of maximum daily precipitation have been examined in greater detail in relation to rainfall-generated floods, and the results have been used to estimate peak river discharge. Much of this research was conducted in the 1970s and 1980s. At that time, time series compiled by Rustamov, Gashgay, and others from various hydrometeorological observations met the stationarity criterion. Climate change may affect the formation of extreme precipitation, but the direction of its effects differs among regions. Although most series show no statistically

significant linear trend, some exhibit heterogeneity in their mean and variance. Statistical homogeneity and stationarity must therefore be assessed separately. Reliable precipitation characteristics are needed to estimate peak rainfall-flood discharge in small catchments with limited or no hydrological observations. Refining the precipitation parameters used in existing calculation methods, while accounting for regional characteristics, reduces uncertainty in peak-discharge estimates and provides better-founded design inputs for hydraulic structures. These considerations demonstrate the need to investigate maximum daily precipitation.

Object and subject of the research. The research objects are heavy rainfall events and maximum daily atmospheric precipitation observed in Azerbaijan. The subject comprises the spatiotemporal variability of maximum daily precipitation, the statistical properties of long-term observation series, and the patterns governing precipitation estimates at different exceedance probabilities. The study evaluates the spatial distribution and interannual and intra-annual variability of maximum daily precipitation, as well as the homogeneity and stationarity of observation series. It also examines methods for estimating extreme precipitation in ungauged areas and their application to determining peak discharge during rainfall-generated floods.

Aim and objectives of the research. The principal aim of the dissertation is to develop a calculation procedure for estimating rare-event values of maximum daily precipitation, accounting for temporal variability and spatial distribution across Azerbaijan, and thereby improve the accuracy of estimating rainfall-generated peak discharge. To achieve this aim, the following objectives were established:

– to assess the homogeneity and stationarity of maximum daily precipitation series under changing climatic conditions;

– to analyze the monthly distribution of maximum daily precipitation across regions;

– to calculate rainfall intensity and analyze intensity–duration–frequency relationships;

– to identify spatial patterns in the statistical parameters of maximum daily precipitation series;

– to calculate precipitation quantiles at different exceedance probabilities for heterogeneous observation series;

– to estimate rare-event precipitation values at locations without observational data;

– to refine the parameters of the maximum-intensity formula to improve estimates of peak discharge in flood-prone rivers.

Research methods. The study employed geographical comparison, generalization, interpolation, extrapolation, mathematical statistics, and cartographic methods.

Main propositions submitted for defense:

1. Spatiotemporal variability of maximum daily precipitation and truncated exceedance-probability curves for heterogeneous observation series;

2. A calculation procedure for precipitation quantiles at different exceedance probabilities in locations without observational data;

3. Reduction of errors in peak-discharge estimation by refining the parameters of the maximum-intensity formula.

Scientific novelty of the research.

– Discrepancies between empirical and analytical exceedance-probability curves were identified for some maximum daily precipitation series;

– Spatial distribution patterns of the mean and coefficient of variation of maximum daily precipitation series were determined;

– Calculation procedures for estimating precipitation quantiles at different exceedance probabilities were developed according to the statistical structure of observation series;

– The principal parameters of analytical exceedance-probability curves were generalized for estimating rare-event precipitation where observational data are unavailable;

– The accuracy of peak-discharge calculations was improved by refining the parameters of the maximum-intensity formula.

Theoretical and practical significance of the research. The theoretical significance of this study lies in identifying the patterns of spatiotemporal variability, statistical structure, and formation of

maximum daily precipitation values at different exceedance probabilities across Azerbaijan. The findings contribute to understanding regional characteristics of extreme atmospheric precipitation, the statistical analysis of heterogeneous observation series, and the substantiation of precipitation characteristics used in hydrological calculations.

The practical significance of the research lies in estimating maximum daily precipitation at different exceedance probabilities in areas with insufficient or no observations and in assessing peak discharges of rainfall-generated floods in small rivers and ephemeral watercourses. The results may be used in designing bridges, culverts, stormwater drainage systems, and other hydraulic engineering structures, as well as in flood-hazard assessment and studies of regional manifestations of climate change.

Presentation and application of the research findings. The main propositions and findings of the dissertation were presented and discussed at scientific seminars of the Faculty of Geography of Baku State University and the Institute of Geography of the Ministry of Science and Education of the Republic of Azerbaijan, as well as at the 6th International Scientific and Technical Conference 'Modern Problems of Water Management, Environmental Protection, Architecture and Construction' (Tbilisi, 2016); the Republican Scientific and Practical Conference 'Geographical Problems of the Regions of Azerbaijan' (Baku, 2016); the XX Republican Scientific Conference of Doctoral Students and Young Researchers (Baku, 2016); the International Scientific and Practical Conference 'Water Resources, Hydraulic Structures and the Environment', dedicated to the centenary of the Shollar–Baku water supply complex (Baku, 2017); the Republican Scientific and Practical Conference 'Global Economic Conditions and the Economic-Geographical Position of Azerbaijan', dedicated to the 94th anniversary of the birth of national leader H. Aliyev (Baku, 2017); the XXI Republican Scientific Conference of Doctoral Students and Young Researchers (Baku, 2017); the International Technical and Scientific Conference 'Natural Disasters and Human Life Safety' (Baku, 2017); the Republican Scientific and Practical Conference 'Strategic Road Maps and

Geographical Research', dedicated to the 95th anniversary of the birth of national leader H. Aliyev (Baku, 2018); and 'Развитие географических исследований в Беларуси в XX-XXI веках' (Minsk, Belarus, 2021), among others.

A total of 25 scientific articles and conference papers have been published on the subject of the dissertation.

Institution where the dissertation was carried out. The dissertation was completed at the Department of Hydrometeorology, Faculty of Geography, Baku State University.

Structure of the dissertation. The dissertation consists of an introduction, four chapters, conclusions, and a list of references. The work comprises 185 pages and contains 27 figures, 11 maps, 15 graphs, 5 equations, 22 tables, and 151 references. The introduction occupies 4 pages; Chapter I, 32 pages; Chapter II, 42 pages; Chapter III, 28 pages; Chapter IV, 28 pages; the conclusions, 2 pages; and the bibliography, 15 pages. Excluding tables, graphs, figures, and references, the work contains 220,162 characters.

MAIN CONTENT OF THE RESEARCH

The introduction describes the relevance and state of research on the topic, the aims and objectives, the main propositions submitted for defense, scientific novelty, theoretical and practical significance, and the presentation and application of the research findings.

Chapter One of the dissertation provides a brief account of the **"Climatic conditions of Azerbaijan"** and notes the outstanding contributions of V.I. Figurovsky, A.M. Shikhlinsky, A.A. Madatzade, and A.J. Ayyubov to the study of the country's climate. Taking into account atmospheric processes over Azerbaijan and neighboring regions, together with the climatic characteristics of all its natural regions, the territory was divided into ten synoptic-climatic regions.

Total solar radiation in Azerbaijan ranges from 120 to 160 kcal/cm^2. Maximum temperatures are observed in July and the first half of August, whereas minimum temperatures generally occur in

January. Annual precipitation ranges from 200 to 1,800 mm and averaged 462 mm during the reference climatic period (1961–1990).

Global warming, which began in the 1970s, is also evident in Azerbaijan. In different regions, the onset of a significant rise in air temperature occurred between 1995 and 1998. Compared with 1961-1990, the country's mean annual air temperature increased by 0.7°C during 1991-2014. The area of glaciers in the Greater Caucasus has decreased. According to research conducted at the Institute of Geography, annual precipitation has declined by 3-15% in many regions of the country over the past 40 years.

One of the principal characteristics of atmospheric precipitation is the maximum daily precipitation amount. A. M. Shikhlinsky prepared a map of daily precipitation maxima for Azerbaijan and showed similarities between the spatial distributions of this indicator and annual precipitation. Across most of the country, the highest values occur mainly from April to October, and in the Lankaran natural region from May to October.

It has been established that, compared with 1961-1990, the number of days with daily precipitation exceeding 10, 15, 20, 25, and 30 mm in the Caspian coastal zone increased by a factor of 1.3-1.6 during 1991-2017. The frequency of such days increased in autumn and winter but decreased in spring and summer.

Analysis of upper-air pressure charts showed that heavy rainfall occurs during meridional changes in the thermobaric field of the middle troposphere, when cyclones form over the Black Sea and the Anatolian Peninsula. Meteorological and aerological synoptic data indicate that intense rainfall in Azerbaijan occurs predominantly (92%) during the passage of cold atmospheric fronts. When precipitation-bearing synoptic systems enter the country from the Black Sea via Georgia, heavy rainfall generally affects western Azerbaijan (45%); when they arrive from the Caspian Sea, it mainly affects eastern Azerbaijan (28%). When cold air masses enter simultaneously from the west and east, precipitation is recorded across the country (18%). Atmospheric processes over Azerbaijan are strongly influenced by the large-scale circulation processes of Synoptic Region I of the Northern Hemisphere. Most heavy rainfall

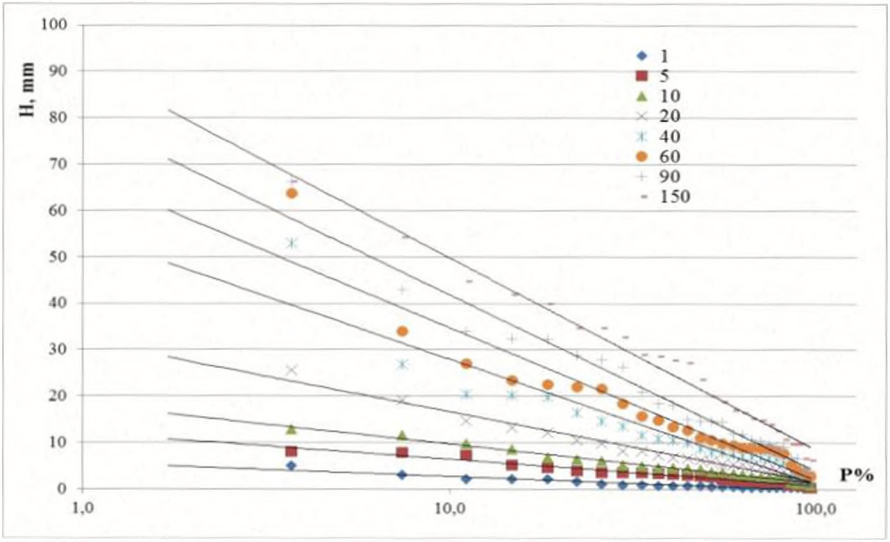
events and associated debris flows (76.2%) occur under meridional synoptic circulation, while the remainder (23.8%) occur under zonal circulation. The country's high mountain ranges mechanically influence atmospheric circulation and favor the formation of strong vertical air currents over mountainous areas.

Various methods are used to design stormwater drainage and calculate peak discharges of rainfall-generated floods in small rivers; rainfall intensity is a key parameter in all the calculation formulas. Rainfall characteristics (depth, duration, and intensity) are determined through statistical processing of pluviograph records. The resulting values are generalized as intensity–duration–frequency (IDF) curves or their analytical expressions.

Data from 22 pluviographs installed and operated in Azerbaijan at different times were processed using the established methodology. Observation records range from 7 to 30 years in length. Intensity–duration–frequency curves for the Lankaran Zonal Meteorological Station are presented below (Graph 1).

Similar curves were constructed for other stations with observation periods exceeding 30 years (Mashtaga, Lankaran, and others).

Chapter Two of the dissertation is devoted to the analysis of the **"Spatiotemporal patterns of maximum daily precipitation"**. The study is based on maximum daily precipitation observations from 75 meteorological stations of the National Hydrometeorological Service under the Ministry of Ecology and Natural Resources, covering 1961-2018, together with pluviograph records.



Source: The graph was prepared by the author based on observational data provided by the National Hydrometeorological Service of the Ministry of Ecology and Natural Resources of the Republic of Azerbaijan.

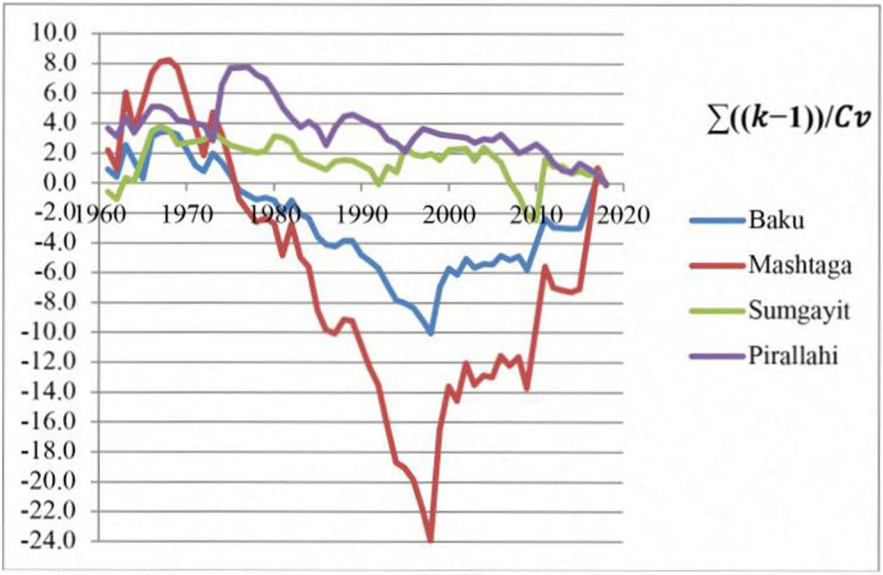
Graph 1. Intensity–duration–frequency curves (Lankaran Zonal Station)

Long-term fluctuations in hydrometeorological variables were analyzed using cumulative departure curves and correlation matrices. The homogeneity of the series was tested using statistical criteria, and stationarity was evaluated by linear trend analysis.

The cumulative departure curves for the Absheron Peninsula (Graph 2) fall into two groups because maximum daily precipitation in coastal areas (Pirallahi and Sumgayit stations) and inland areas (Baku and Mashtaga stations) is formed under different synoptic processes. All correlation coefficients between maximum daily precipitation series are below 0.7, meaning that the relatively short observation records cannot reliably be extended.

The statistical significance of linear trends was evaluated using Student's t-statistic. On the Absheron Peninsula, none of the linear trends is statistically significant. Elsewhere in Azerbaijan, maximum daily precipitation series exhibit trends of differing signs: positive trends were identified in 11 series, negative trends in 14, and no

trend in 4. Of these 29 series, only one (Salyan) shows a statistically significant positive trend. Trends in the remaining series are not statistically significant; this does not justify a conclusion of sustained increase or decrease, but neither does it establish complete stationarity.



Source: The graph was prepared by the author based on observational data provided by the National Hydrometeorological Service of the Ministry of Ecology and Natural Resources of the Republic of Azerbaijan.

Graph 2. Cumulative departure curves of maximum daily precipitation at meteorological stations on the Absheron Peninsula

A comparison of the mean maximum daily precipitation for 1961-1990 and 1991-2018 (Table 1) reveals changes in different directions across Absheron. Values increased from 28.4 to 33.4 mm (+17.6%) in Baku and from 31.7 to 33.2 mm (+4.73%) in Mashtaga, but decreased from 30.5 to 24.9 mm (−18.4%) in Pirallahi and from 26.6 to 26.4 mm (−0.75%) in Sumgayit. Both the direction and magnitude of change therefore differ within the peninsula. These differences may be related to synoptic processes and local conditions

in its inland and coastal areas; statistically insignificant trends, however, do not confirm sustained changes.

Analysis of the monthly occurrence of maximum daily precipitation showed that, in all regions, daily precipitation maxima occur most frequently in autumn, particularly in September and October. The lowest frequency is characteristic of winter. With the exception of the Kura-Araz Lowland, the frequency is very low in early spring (March and April) in all regions.

Table 1

Changes in maximum daily precipitation during 1991-2018 compared with 1961-1990

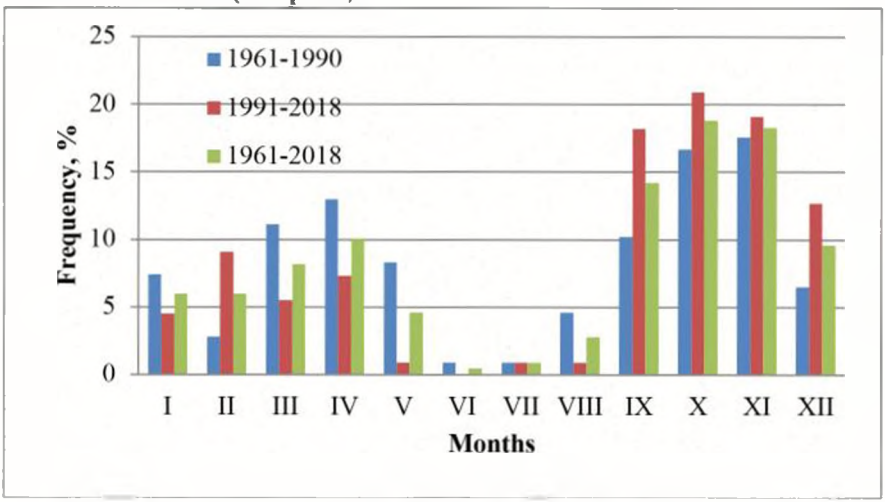
№	Station	Mean annual maximum daily precipitation (1961–1990)	Mean annual maximum daily precipitation (1991–2018)	Change in mean annual maximum daily precipitation	
				mm	%
1	Baku	28.4	33.4	5.0	+17.6
2	Mashtaga	31.7	33.2	1.5	+4.73
3	Pirallahi	30.5	24.9	5.6	-18.4
4	Sumgayit	26.6	26.4	0.2	-0.75

Source: The table was prepared by the author based on observational data provided by the National Hydrometeorological Service of the Ministry of Ecology and Natural Resources of the Republic of Azerbaijan.

Comparison of the periods 1961-1990 and 1991-2018 on the Absheron Peninsula (Graph 3) shows that the occurrence of maximum daily precipitation decreased by 18.1% in spring and increased by 13.7% in autumn. The highest occurrence shifted from November in the first period to October in the second. Thus, variability is not confined to long-term averages; the seasonal distribution of precipitation maxima has also changed. These differences may be interpreted as possible regional manifestations of climate change.

It was found that maximum daily precipitation on the Absheron Peninsula generally increases in winter (December-February). March marks a transition from increasing to decreasing values, with virtually no trend; precipitation decreases from April to June,

increases again in July, and decreases in August. September and October are generally characterized by increases, whereas November shows a decrease (Graph 3).



Source: The graph was prepared by the author based on observational data provided by the National Hydrometeorological Service of the Ministry of Ecology and Natural Resources of the Republic of Azerbaijan.

Graph 3. Monthly frequency of maximum daily precipitation on the Absheron Peninsula

In applied hydrometeorology, particular attention is paid to rare maximum daily precipitation events. Their magnitudes are determined from analytical exceedance-probability curves. In this section, statistical parameters of maximum daily precipitation series from 50 meteorological stations were estimated using the method of moments and the maximum likelihood method. The coefficients of variation obtained by the two methods differ by only 0.01–0.02. Therefore, either method can be used to estimate the statistical parameters of maximum daily precipitation series. However, because the maximum likelihood estimates are statistically more stable, they were used in subsequent calculations and geographical generalizations.

The relative errors of the sample mean, coefficient of variation, and coefficient of skewness were also assessed. For series of extreme

hydrometeorological variables, the critical threshold of permissible error may reach 20%. The relative error of the mean exceeds 10% at only six stations (12% of all stations). The relative error of the coefficient of variation ranges from 10.2% (Baku) to 22.5% (Gobustan), and is below 15% at 33 stations (66%).

For each of the 50 maximum daily precipitation series, an empirical exceedance-probability curve and two analytical curves (a lognormal curve and the Kritsky–Menkel three-parameter gamma curve) were constructed. Visual comparison of the empirical and analytical curves yielded four groups:

1. The lognormal and KritskyMenkel three-parameter gamma curves approximate the empirical exceedance-probability curves equally well (Goychay, Tovuz, Zagatala, Astara, etc.). These series account for 26% of the total.

2. The Kritsky–Menkel three-parameter gamma curve provides a better fit for 48% of the empirical curves.

3. The lognormal curve provides a better fit for only 6% of the empirical curves (Alat, Imishli, Maraza).

4. Because the observation series are heterogeneous, neither analytical exceedance-probability curve satisfactorily approximates the empirical data (Kurdamir, Mashtaga, Neft Dashlari, Aghstafa, etc.). This group represents 20% of the series.

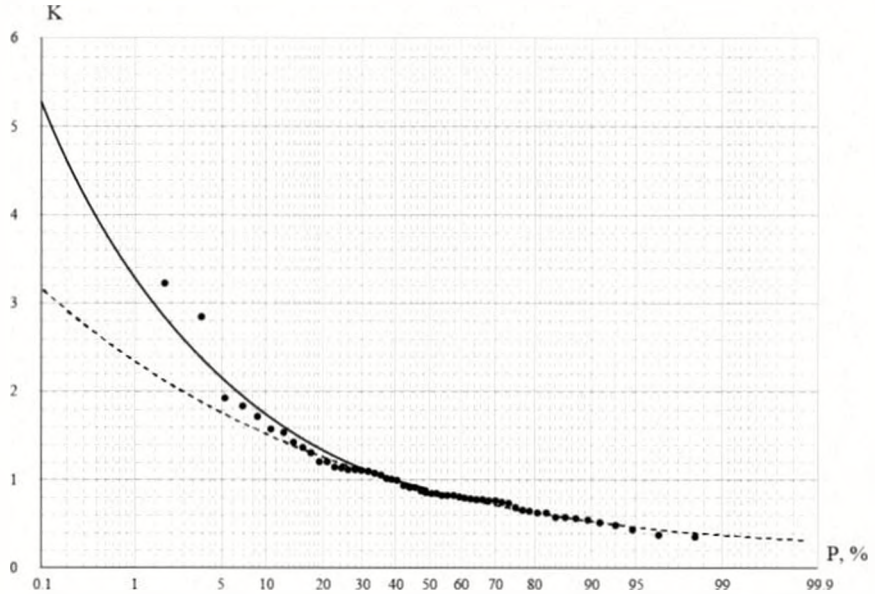
The analysis therefore indicates that the Kritsky–Menkel three-parameter gamma curve is preferable for fitting empirical exceedance-probability curves of maximum daily precipitation in Azerbaijan. It satisfactorily approximates 74% of the observation series. This conclusion is also supported by a comparative goodness-of-fit assessment of the lognormal and Kritsky–Menkel three-parameter gamma curves against the empirical curves. The Pearson criterion, widely used in international practice, was applied to assess their fit.

It should be noted that several points representing rare events (usually one or two points) in the upper part of the empirical curves deviate sharply from the lognormal and Kritsky–Menkel three-parameter gamma curves (Tartar, Bilasuvar, Ismayilli, Lankaran, etc.). Such series constitute 16% of the total.

Truncated distribution curves are used to determine hydrometeorological variables at different exceedance probabilities from observation series (20%) whose hydrometeorological homogeneity has been disrupted by natural or anthropogenic factors.

In this approach, a portion of the observed values is excluded from the calculations, and the exceedance-probability curve—or, more precisely, the analytical truncated exceedance-probability curve-is fitted to the remaining observations. For maximum daily precipitation, only the upper part of the series arranged in descending order, that is, the largest values, is used.

The applicability of the truncated gamma distribution to estimating rare maximum daily precipitation values on the Absheron Peninsula was investigated (Graph 4).



Source: The graph was prepared by the author based on observational data provided by the National Hydrometeorological Service of the Ministry of Ecology and Natural Resources of the Republic of Azerbaijan.

Graph 4. Truncated gamma exceedance-probability curve of maximum daily precipitation for Sumgayit station

Graph 4 clearly shows that the truncated gamma exceedance-probability curve fits the empirical points better than the full gamma curve. This indicates that analytical truncated gamma exceedance-probability curves can be used to estimate low-exceedance-probability values from heterogeneous maximum daily precipitation series at observation stations in Azerbaijan.

Because time series compiled from observations at individual meteorological stations are relatively short, the information they contain is insufficient to estimate hydrometeorological variables at different exceedance probabilities with high reliability. One approach to improving the accuracy and reliability of the estimates is the joint analysis of observations from neighboring stations. In doing so, it should be recognized that maximum daily precipitation at each station in a group differs from that at the other stations for two reasons. First, even within a climatically homogeneous region, long-term fluctuations in maximum daily precipitation are not fully synchronous: heavy rainfall does not occur at all stations at the same time. This introduces a random component of variability. Second, differences in climatic conditions, including synoptic processes, introduce a geographical component. The principal purpose of joint analysis is to estimate these two components separately and use them in calculations.

In this study, the parameters of maximum daily precipitation series at four stations on the Absheron Peninsula were also refined using joint analysis, and the applicability of this method to the calculations was investigated.

According to the joint-analysis methodology, the total variance of each parameter of a maximum daily precipitation series (mean, coefficient of variation, or coefficient of skewness) has two components:$\varepsilon^2_{\ddot{u}mum}$)

$$\varepsilon^2_{\ddot{u}mum} = \varepsilon^2_{t\partial s} + \varepsilon^2_{co\check{g}} \qquad (1)$$

where the first term denotes the random variance of the parameter under consideration (mean, coefficient of variation, or coefficient of skewness), and the second denotes its geographical variance.$\varepsilon^2_{t\partial s}$ $\varepsilon^2_{co\check{g}}$

The total dispersion (variance) of each parameter is determined separately using the following formula:

$$\varepsilon^2_{\ddot{u}mum} = \frac{\sum_{i=2}^{k}(A_i - \bar{A})^2}{k-1} \qquad (2)$$

where A_i is the statistical parameter of maximum daily precipitation at station i; the mean of that parameter is calculated across all stations; and k is the number of stations.$\bar{A}$

The random variance of any parameter is defined as the arithmetic mean of the corresponding variances (absolute errors) calculated separately for each observation station. Variances of the mean, coefficient of variation, and coefficient of skewness are estimated using standard formulas. Geographical variance is calculated as the difference between total and random variance:

$$\varepsilon_{co\breve{g}} = \varepsilon_{\ddot{u}mum} - \varepsilon_{t\partial s} \qquad (3)$$

where the terms denote geographical, total, and random variance, respectively.$\varepsilon_{co\breve{g}}\, \varepsilon_{\ddot{u}mum} \varepsilon_{t\partial s}$

One of the main conditions for applying joint analysis is that, for each parameter under consideration, geographical variance must be smaller than random variance:

$$\varepsilon_{co\breve{g}} \leq \varepsilon_{t\partial s} \qquad (4)$$

Calculations using the joint-analysis methodology were carried out in two stages. In the first stage, four stations operating on the Absheron Peninsula were combined into one group, and the total variances of the parameters and their random and geographical components were determined for each station (Table 2).

Table 2.

Results of variance calculations using the joint-analysis methodology

Group number	Stations	Parameters	Mean parameter value across all stations	Variance		
				Total	Random	Geographical
1	Baku, Mashtaga, Sumgayit, Pirallahi	X_{ot}	30,1	9,607	1,952	7,655
		Cv	0,50	0,003	0,084	-0,081
		Cs	1,75	0,295	0,553	-0,258
2	Baku, Sumgayit, Pirallahi	X_{ot}	28,7	3,205	2,021	1,184
		Cv	0,52	0,001	0,055	-0,054
		Cs	1,91	0,289	0,574	-0,285

Source: The table was prepared by the author based on observational data provided by the National Hydrometeorological Service of the Ministry of Ecology and Natural Resources of the Republic of Azerbaijan.

As shown in Table 2, the principal condition for joint analysis (Equation 4) is not satisfied for the mean maximum daily precipitation: geographical variance exceeds random variance and accounts for 79.7% of the total variance.

In the second stage, Mashtaga station was excluded from the group, and the observations from the remaining three stations (Baku, Sumgayit, and Pirallahi) were jointly analyzed. The results show that the principal condition (4) is then satisfied for all parameters. As Table 2 indicates, the variability (coefficients of variation) of the maximum daily precipitation series at these three stations is almost identical. It may therefore be assumed that the observations at all three stations belong to a common parent population. Accordingly, the series were combined into a single series and its statistical parameters calculated: mean = 28.8 mm, Cv = 0.52, Cs = 2.08, and Cs/Cv = 4. The 1% exceedance-probability precipitation estimated from the analytical curve of the combined series is 79.5 mm. The corresponding 1% values calculated from the individual series differ

from this value by only 0.1–3.1%, confirming the practical relevance of the approach.

This methodology enables the joint analysis of observations from stations with similar statistical parameters and may also be applied in the Kura-Araz Lowland. More generally, accounting for long-term and intra-annual variability in maximum daily precipitation, together with spatial differences in its statistical characteristics, is important for estimating peak rainfall-flood discharges in small river basins with limited hydrological observations. Regional precipitation estimates at specified exceedance probabilities provide a basis for selecting design parameters.

Chapter three of the dissertation, **"Estimation of maximum daily precipitation in the absence of observational data"** develops the corresponding calculation procedures.

Methods currently used to estimate maximum daily precipitation where observations are unavailable fall into two groups: the parameter method and the transfer-coefficient method. The transfer-coefficient method was used in the former USSR, including Azerbaijan. In Western countries, the parameter method is applied and is considered better justified scientifically. This study develops a calculation procedure based on the parameter method. Accordingly, all three parameters of the Kritsky–Menkel three-parameter gamma distribution the mean maximum daily precipitation, coefficient of variation, and ratio of the coefficient of skewness to the coefficient of variation were estimated for each of the 50 observation series using maximum likelihood, and the resulting estimates were generalized.

The long-term mean of maximum daily precipitation is the average of the daily maxima recorded in individual years. It enables comparisons among stations but does not replace the design precipitation depth for a rare event. Long-term mean maximum daily precipitation ranges from 19.5 mm at Neft Dashlari to 113 mm at Lankaran, a difference of approximately 5.8 times. The value at 50% exceedance probability is 34 mm. This spatial unevenness requires regional characteristics to be considered. The distribution of mean

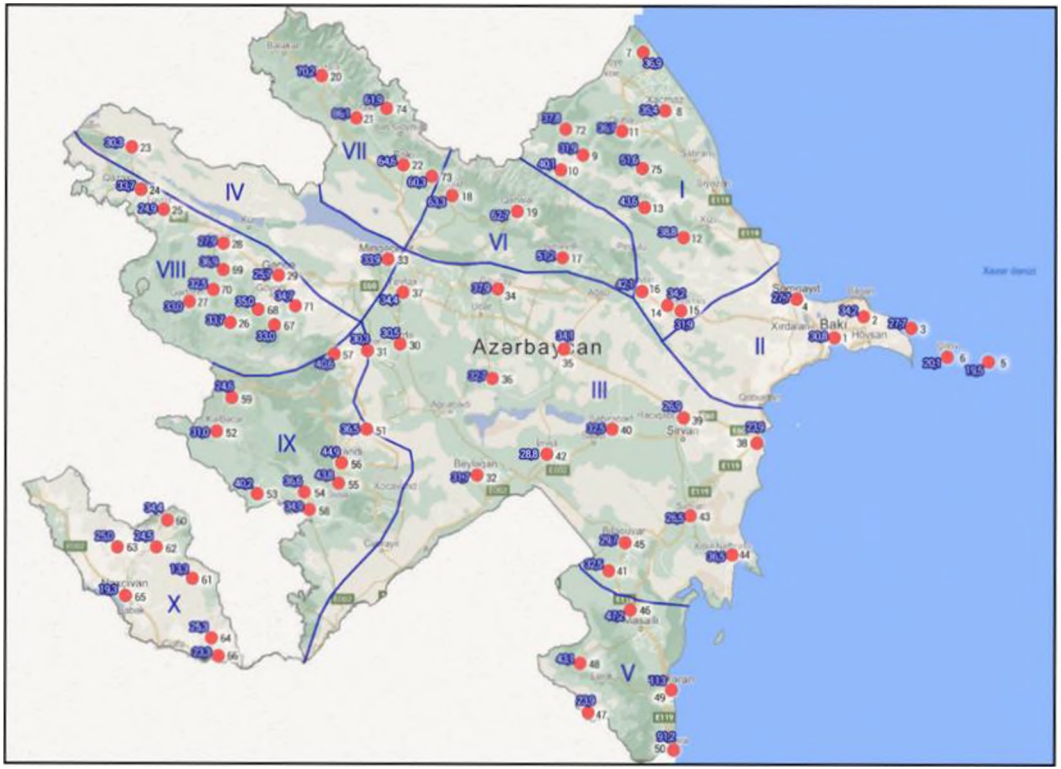
values was analyzed by ten synoptic-climatic regions distinguished by atmospheric processes and climate: (1) Guba-Khachmaz, (2) Absheron-Gobustan, (3) Central Aran, (4) Jeyranchol-Bozdag, (5) Lankaran-Astara, (6) Oghuz-Ismayilli, (7) Zagatala-Sheki, (8) Gazakh-Ganja, (9) Mountainous Karabakh and Kalbajar-Lachin, and (10) Nakhchivan (Figure 1).

No relationship suitable for practical calculations was found between the mean maximum daily precipitation and station elevation above sea level in any of the ten synoptic-climatic regions. This indicates that elevation alone is insufficient for regional generalization. A map of mean maximum daily precipitation across Azerbaijan was prepared using GIS technology and ArcGIS software.

Spatial differences in maximum daily precipitation are also reflected in its statistical parameters: the coefficient of variation ranges from 0.22 at Astara to 0.81 at Khachmaz. Its 50% exceedance-probability value is 0.38. This range characterizes regional variability.

A relationship between the coefficient of variation and station elevation suitable for practical calculations was found only in the Gazakh–Ganja region, where the correlation coefficient is 0.83. This result shows that a single elevation-dependent relationship cannot be applied everywhere when generalizing statistical parameters regionally. A map of the coefficient of variation of maximum daily precipitation was also prepared for Azerbaijan.

The ratio of the coefficient of skewness to the coefficient of variation ranges from 1.0 to 6.0. The value of this ratio at 50% exceedance probability is 3.5.



Source: The graph was prepared by the author based on observational data provided by the National Hydrometeorological Service of the Ministry of Ecology and Natural Resources of the Republic of Azerbaijan.

Figure 1. Distribution of mean maximum daily precipitation by synoptic-climatic region

Chapter four of the dissertation is devoted to **"Estimation of peak discharges of rainfall floods".** The most detailed studies of rainfall-flood formation were conducted by S.H. Rustamov (1960), M.A. Mammadov (1989), and R.N. Mahmudov (2001). They determined mean flood duration, frequency, timing, the flood coefficient, and the contribution of flood runoff to annual runoff in different regions. S. H. Rustamov also examined regional features of rainfall-flood formation.

A brief review of studies on rainfall floods and the formation of their peak discharges in Azerbaijan suggests that, although the general genetic theory of rainfall-flood formation is known, the role of physical-geographical factors under Azerbaijani conditions has not yet been investigated in sufficient detail using modern methods.

Peak discharges of rainfall floods are estimated under three conditions, depending on the availability of hydrological observations: sufficient data, limited data, and no data. In practice, the greatest difficulties arise when estimating runoff characteristics for ungauged rivers. Various empirical formulas and runoff coefficients are used to calculate rainfall-flood peak discharges in such rivers.

The World Meteorological Organization's guidance on hydrological practice also proposes methods for estimating peak rainfall-flood discharges. These fall into two broad groups: empirical methods (reduction and regression formulas, including polynomial regression equations) and methods based on rainfall–runoff models (the rational method, the maximum-intensity formula, and unit-hydrograph methods).

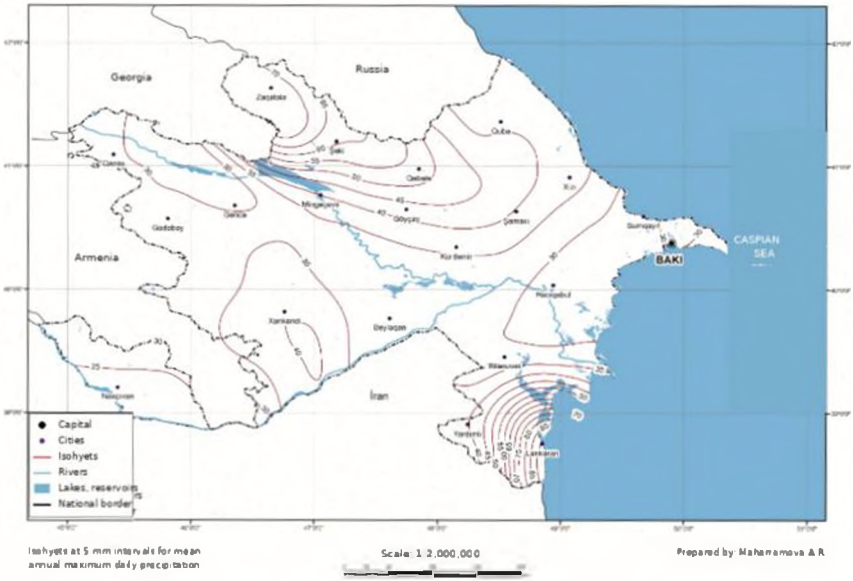


Figure 2. Map of mean maximum daily precipitation in Azerbaijan

The rational method, widely used in the United States and other Western countries, corresponds to the maximum-intensity method used in the former USSR. D. L. Sokolovsky (1968) noted that, rather than proposing new formulas for estimating peak discharge, priority should be given to studying flood-formation processes in different physical-geographical regions and refining the regional parameters of existing formulas.

Two types of formulas are currently used in Azerbaijan to estimate rainfall-flood peak discharges for ungauged rivers: reduction formulas and maximum-intensity formulas. Because reduction relationships have been studied relatively thoroughly and their construction presents no technical difficulties, reduction formulas were not examined in this study.

For small rivers with mean catchment elevations of 500–2,000 m and catchment areas below 100 km^2, the peak discharge at 1% exceedance probability (Q1%) may be estimated using the following formula:

$$Q_{1\%}=A_{1\%}\varphi H_{1\%} \qquad (5)$$

where Q1% is the peak-discharge modulus at 1% exceedance probability; A1% is the relative maximum runoff modulus at 1% exceedance probability; φ is the runoff coefficient; F is catchment area; and H1% is the maximum daily rainfall depth at 1% exceedance probability.

An earlier comparison of peak discharges calculated using the maximum-intensity formula with observed values for 19 rivers in Azerbaijan showed that calculated values were substantially higher for most rivers (16 rivers): by 58% on average and up to 128%. This was attributed to the fact that observed (actual) peak discharges in small river basins do not always fully represent the true peak values.

This study sought to reduce calculation errors by refining the main parameters (A1%, φ, and H1%) of the maximum-intensity formula (5) used in Azerbaijan.

The relative maximum runoff modulus at 1% exceedance probability (A1%) is obtained from a special table according to the hydromorphometric characteristics of the river channel and the hillslope travel time. For mountain rivers, hillslope travel time had been assumed to be approximately 10 minutes, with the possibility of refinement based on hillslope hydromorphometry and the regional number assigned to precipitation reduction curves. In the present study, hillslope travel time was recalculated for each river and found to range from 52 to 200 minutes. Previously, a value of 60 minutes had been assumed for each of the 19 rivers when calculating peak discharge. Thus, A1% was determined from the special table using the channel hydromorphometric characteristics and recalculated hillslope travel times.

For the entire Caucasus, values of the "composite runoff coefficient" are provided in a special table for 11 soil types occupying the largest areas within river catchments. According to this table, the runoff coefficient ranges from 0.10 for soils widespread in semi-deserts to 0.80 for brown mountain-forest soils with heavy loam texture18.

For the rivers considered, the composite runoff coefficient was selected according to the predominant soil type in each catchment, yielding values from 0.20 to 0.40.

A 1% exceedance-probability value of the annual maximum daily precipitation means a 1% probability that this threshold will be exceeded in any given year, corresponding to a theoretical return period of 100 years; it does not mean that such an event occurs exactly once every 100 years. Unlike the long-term mean, the 1% exceedance-probability value also depends on variation and skewness. Mapping the design rainfall depth is important for small catchments. In this study, a new map was prepared for Azerbaijan using recent data (Figure 3). GIS technologies were used to produce the map, and interpolation was used to estimate maximum daily precipitation at 1% exceedance probability. The corresponding rainfall depth for each river catchment was obtained from this map and incorporated into the maximum-intensity formula with due consideration of regional differences.

Peak discharges for the rivers considered were calculated using the refined parameters (A1%, φ, and H1%). Errors in the calculated peak discharges range from 1% to 238%, with a median error of 38%, a reduction of 9 percentage points compared with the previous 47%. For comparison, earlier calculations produced errors of 4-128% and a median error of 47%, respectively16.

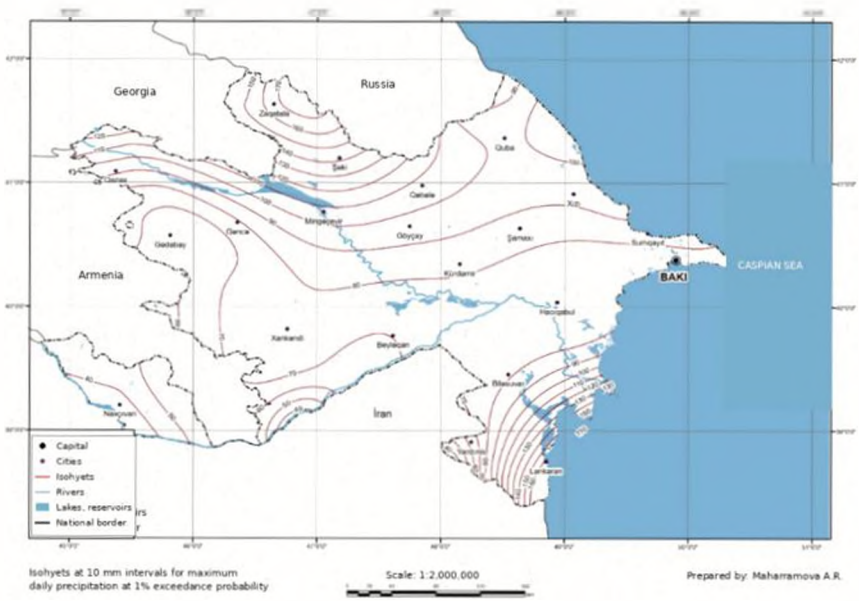


Figure 3. Map of maximum daily precipitation at 1% exceedance probability

CONCLUSIONS

1. Maximum daily precipitation in Azerbaijan generally occurs in autumn, particularly in September-October. On the northeastern slope of the Greater Caucasus and in the Shirvan zone, the maxima occur in September, whereas in other regions they occur in October. The lowest frequency of maximum daily precipitation is characteristic of winter.

On the Absheron Peninsula, compared with 1961-1990, the frequency of maximum daily precipitation decreased by 18.1% in spring and increased by 13.7% in autumn during 1991-2018. The highest frequency occurred in November in 1961-1990 and in October in 1991-2018. The shift in the intra-annual distribution of maximum daily precipitation in the later period is probably associated with climate change [9;10;13;15;17].

2. Rainfall intensity was calculated from pluviograph records, and the results were generalized as intensity–duration–frequency curves. The small number of pluviographs and the short observation records complicate the spatial and temporal generalization of the calculated rainfall intensities [2;3;8].

3. Across all regions, 6% of maximum daily precipitation series are statistically non-homogeneous with respect to the mean, and 24% with respect to variance. Although positive and negative linear trends occur in the series examined, a statistically significant positive trend was found in only one series (Salyan) [4;5;6].

4. The Kritsky–Menkel three-parameter gamma curves provide a satisfactory approximation to the empirical exceedance-probability curves for 74% of the observation series. To improve the accuracy of estimating maximum daily precipitation at 1% exceedance probability, the applicability of joint analysis was investigated in Azerbaijan for the first time using data from four observation stations on the Absheron Peninsula for 1961-2018. The estimates obtained by this method were found to be more reliable because they incorporate additional information from neighboring stations.

5. To estimate the return periods of precipitation more accurately for non-homogeneous series, truncated gamma analytical exceedance-probability curves were applied in Azerbaijan for the first time. These curves approximate the upper portions of the empirical exceedance-probability curves more closely than the complete gamma curves [1;14;16;18;19].

6. To estimate rare maximum daily precipitation values at locations without observations, information was generalized for all three parameters: the mean, coefficient of variation, and ratio of the coefficient of skewness to the coefficient of variation. New maps were prepared for the first two parameters, while the third parameter was averaged by synoptic-climatic region [3;14;16;19].

7. To improve estimates of peak discharges for flood-prone ungauged rivers and ephemeral watercourses, a new map of maximum daily rainfall depth at 1% exceedance probability the principal parameter of the maximum-intensity formula was prepared using updated data. Two additional parameters, the relative

maximum runoff modulus at 1% exceedance probability and the runoff coefficient, were also refined. The median error of peak discharges calculated with the refined parameters was 38%, which is 9 percentage points lower than the error obtained with the parameters currently used.

RECOMMENDATIONS

1. The regional calculation procedure developed in this study is recommended for estimating peak rainfall-flood discharges in small river catchments and ephemeral watercourses in Azerbaijan where hydrological observations are unavailable or limited.

2. Before estimating rare precipitation events, observation series should be tested for homogeneity and stationarity. Truncated exceedance-probability curves are recommended for non-homogeneous series that are not adequately represented by conventional analytical curves.

3. The refined maximum-intensity parameters and the map of rainfall depth at 1% exceedance probability may be used to estimate peak discharges in small rivers; the median error was reduced by 9 percentage points.

4. When designing bridges, culverts, and stormwater drainage systems, regional differences and exceedance-probability values of maximum daily precipitation should be taken into account, particularly for ungauged catchments.

5. It is recommended that precipitation characteristics used in hydrological calculations be determined on a regional basis, accounting for the spatiotemporal variability of maximum daily precipitation in Azerbaijan. Because long-term changes, seasonal frequencies, and statistical parameters of precipitation maxima differ among synoptic-climatic regions, regional characteristics identified in this study should be used instead of uniform design values for the entire country.

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