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THE CONCEPTUAL MODEL OF CLIMATE CHANGE IN THE REPUBLIC OF AZERBAIJAN

Nazim HUSEYNOV [1*], Jamal HUSEYNOV [1], Zakir GULIYEV [1]

[1] Azerbaijan Airlines CJSC, National Aviation Academy, Department of Aviation Meteorology, Baku, Azerbaijan; nazimmet@mail.ru (N.H.); camal_ huseynov_88@mail.ru (J.H.); zakir956@mail.ru (Z.G.)

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Abstract: The objective of the research is to develop a conceptual approach to the factors influencing the formation of climate change in the territory of Azerbaijan, its impact mechanisms, and the ecological crises they induce. Therefore, in the study, climate change is divided into several stages, with each stage being thoroughly explained using precise factual data. This study provides a comprehensive assessment of the interrelationships and impact mechanisms of ecological crises formed by climate change in the territory of the Republic of Azerbaijan. The results are evaluated using advanced cartographic and mathematical-statistical processing methods such as ArcGIS, SPSS, Stock Stat, and MS Excel. The air temperature, atmospheric precipitation, and physical characteristics of glaciers for the periods 1961-1990, 1991-2020, 1981-2010, and 2011-2023 were compared. The study examines the climate change process in the country's territory in three stages: formation, impact mechanisms, and outcomes. For the first time, a conceptual model of climate change specific to Azerbaijan was developed based on these features. An increase in the volume of exploited groundwater resources has been observed across the country. Under the influence of climate change, shifts in wind direction and average speeds have occurred. The scientific work presents a map delineating the approximate impact zones of warming effects. The air temperature increase of 0.8°C was accompanied by a 4% decrease in precipitation. Climate change has resulted in a 15-23% reduction in glaciers over the past seven years, an increase in drought, and an acceleration of desertification. Approximately 36.5% of the country's surface area is projected to be at risk of dangerous atmospheric processes.

Keywords: Climate change, temperature increase, lightning, hail, GIS technology, glaciers, landscape landslides, fluctuations in the Caspian Sea level

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INTRODUCTION

The South Caucasus region, where the Republic of Azerbaijan is located, has a complex physical-geographical position, making it possible to observe the multifaceted impacts of global warming (Mammadov et. al., 2009). Currently, under the influence of climate change, the number, frequency, and extent of ecological crises in the region, including the territory of Azerbaijan, are continuously increasing (Ismayilov & Suleymanov, 2024).

Modern warming shares both similar and distinct characteristics with climate change that occurred during geological eras. Climate changes during the Earth's geological eras were characterized by well-known glacial and interglacial periods (McGee, 2020). These periods have played a decisive role in shaping the Earth's climate history and driving the evolution of ecosystems up to the modern era (Imbrie & Imbrie, 1986). During glaciation (global dimming) periods, ice sheets expanded to continental scales, the physical parameters of glaciers in the Arctic and Antarctic increased rapidly, sea levels dropped (sometimes by as much as 120 meters), and global temperatures decreased by an average of 4-8°C (Lamb, 2011). In contrast, during warming periods, global temperatures rose, ice sheets melted, and sea levels increased, forming new coastlines (Driese et al., 2021). Warming was primarily associated with volcanic activity, increased carbon dioxide levels in the atmosphere, and solar activity. Examples of such warming periods include the Triassic-Jurassic and the Eocene thermal maximum (55 million years ago). *Such climate changes on Earth have occurred due to natural causes, influenced by Milankovitch cycles.* (McGee, 2020; Lamb, 2011). Such systematization of climate change significantly influences the determination of its development and consequences, as well as the formulation of mitigation and adaptation measures. However, in recent years, there have been considerable disagreements regarding the identification of anthropogenic factors and their impacts (Immerzeel et al., 2010). Modern climate change is manifested with distinct characteristics across various regions of the Earth. Their primary impacts are observed in mid-latitude regions, one of which is the South Caucasus (Tashilova et al., 2019; Abshaev et al., 2003). Azerbaijan, with its unique physical and geographical position within this region, stands out from other areas. Climate change occurring in this region and its impacts have not yet been modeled. Despite the existence of studies by several local and regional researchers in specific fields, this issue has not been consolidated into a concrete conceptual model to date.

* Corresponding author

Objective

The aim of the research is to develop a conceptual model of the factors influencing the formation of climate change in Azerbaijan, their impact mechanisms, and the resulting ecological crises. Accordingly, the study divides the climate change process into several stages in alignment with the conceptual model, providing a detailed explanation of each stage with precise factual analysis.

MATERIALS AND METHODS

In this study, the impacts of climate change were analyzed using data from approximately 70 ground-based observation (hydrometeorological) stations of the National Hydrometeorology Service (https://eco.gov.az/az/hidrometeorologiya/fealiyyet-istiqametleri; https://neco.gov.az/ekoliji-fealiyyet-istiqametleri/hidrometeorologiya; https://www.stat.gov.az/source/environment/), and satellite-reanalysis datasets (https://power.larc.nasa.gov/data-access-viewer/). The initial observation data used in the analyses were collected from annual bulletins, periodic scientific publications, and electronic resources (https://climate.nasa.gov/vital-signs/global-temperature/?intent=121; https://www.ipcc.ch/library/; https://wmo.int/resources/documents). The results obtained from the analyses were evaluated using advanced statistical processing methods in SPSS, Stock Stat, and MS Excel. Mathematical-statistical and cartographic methods were applied in the analyses.

The map was processed using GIS technology (ArcGIS Pro 3.1.3). The DEM files used in GIS analyses have a resolution of 30 m and are based on Landsat and Sentinel satellite images (https://opentopography.org/). In glacier studies, DEM files with a resolution of 1.5 m from the Azersky satellite were utilized (https://azercosmos.az/az). The tables and graphs presented in the study were processed in MS Excel, while the maps were developed in ArcGIS software. For the first time, a conceptual model was created by systematizing the climate change processes in the territory of the Republic of Azerbaijan.

To identify the impacts of climate change, modern methods were employed in the study of a range of **meteorological** (temperature, precipitation, wind, radiation, albedo, drought, lightning, hail, etc.), **hydrological** (flash floods, water levels, floods, glaciers, etc.), and **physical** (landslides, landscape shifts, marsh formation, salinization, deforestation, etc.) elements. One such method is the 5-year moving average, which is frequently used due to its ability to mitigate the misleading effects of sharp outliers in the instantaneous time phase (various years) on the trend line for random variables with long-term series. In graphs, this metric ensures stable smoothing by accounting for the abrupt jumps of random variables, allowing for the determination of the dynamics of the examined random variable at any given time phase (Willemse, 2009). The moving average is calculated using the following formula:

$$X_{1i} = \frac{X_1+X_2+X_3 \ldots +X_5}{5},\ X_{2i} = \frac{X_2+X_3+X_4 \ldots +X_6}{5}, \ldots$$

Here, X_{1i}, X_{2i} represent the 5-year moving average smoothed values of the random variable for precipitation amounts. (X_1, X_2) etc., denote the year under consideration in the series and the limits of the preceding 5 years, including that year. The coefficient of the smoothed average for the year under consideration is equal to the average of the subsequent 5 years, including that year (Wilks, 2011). The next smoothed value is recalculated as the average of the precipitation amount for that year and the limits of the next 5 years. Thus, the series is completed to the end.

In the study, for determining the anomalies of air temperature (*T*) and precipitation (*P*) at various altitudes (*h*), the following formula can be used to calculate the mathematical mean of the annual average temperature and total annual precipitation for (n) meteorological stations (David, 2005):

$$T_h = \frac{1}{n}\sum_{i=1}^{n} T_i$$

Here, T_i represents the annual average temperature of each station, and *n* (is the total number of meteorological stations. The annual precipitation amount (P_h) at the considered altitude is calculated as follows (David, 2005):

$$P_h = \frac{1}{n}\sum_{i=1}^{n} P_i$$

There, *Pi* represents the average annual precipitation of each station (i=1, 2, …), *h* is the considered altitude, and n is the number of stations. In the study, the statistical homogeneity of time series for temperature and precipitation data across different altitudes (1981-2023) was verified using Fisher's and Student's criteria, and only data from statistically reliable stations were utilized. In Fisher's criterion, the series variance is evaluated, while in Student's criterion, the means of the series values are compared. For this research, the observation series from 70 stations for the years 1981–2022 (2023) were tested, and similar values for the observation series were assessed at 5 % and 10 % significance levels for both criteria. The Student's criterion for the observation series is determined using the following expression:

$$t = \frac{\bar{x}-\bar{y}}{\sqrt{n_1 * \sigma_1^2 + n_1 * \sigma_2^2}} * \sqrt{\frac{n_1 * n_2(n_1+n_2-2)}{n_1+n_2}}$$

There, $\bar{x}$ and $\bar{y}$ represent the mean values of the temperature series divided into two halves during the analysis, while n_1 and n_2 are the respective lengths of the series. σ_1 and σ_2 are the respective mean square deviations of the series. This expression compares the determined t-statistic with critical t-values at α-levels of confidence. If the calculated t-statistic is less than the critical value, the hypothesis of homogeneity of the series is accepted; otherwise, the hypothesis is rejected (Willemse, 2009; Wilks, 2011; David, 2005). The Fisher parameter is used to determine the ratio of the dispersion of the larger series to the smaller one (David, 2005): $F = \frac{\sigma_1^2}{\sigma_2^2}$

There, F represents the Fisher parameter, and σ_1 and σ_2 are the dispersions of the series. In the Fisher criterion, α is compared with critical values at different significance levels, and if the critical value is not exceeded, the hypothesis of homogeneity of the series is accepted. The homogeneity of temperature series has been assessed using both Fisher and Student criteria with 5 % and 10 % confidence levels. Although the dispersion of temperature series from different stations is relatively small, due to sharp differences in the average values over the entire period, the hypothesis of homogeneity is rejected in the case of the Student criterion.

RESULTS AND DISCUSSION

In the South Caucasus region, particularly in the territory of the Republic of Azerbaijan, which has a complex orography, the process of climate change can be divided into three stages: formation, impact mechanism, and outcomes. The causes or formation of climate change, its mechanisms of influence, and the resulting ecological crises should be considered as separate stages. In the initial stage, the greenhouse effect, which drives climate change, and the anthropogenic and natural factors that disrupt atmospheric gas concentrations are global-scale issues. Although the Republic of Azerbaijan's share of global carbon emissions is 0.13% (https://eco.gov.az/az/hidrometeorologiya/fealiyyet-istiqametleri; https://www.ipcc.ch/library/), atmospheric pollution, both globally and locally, remains a significant concern (Molina & Molina, 2012). The next stage involves the effects (impact mechanisms) manifested as a result of these factors. Specifically, global temperature increases, reductions in precipitation, and the acceleration of the spatiotemporal mutation of destructive natural events are observed.

The final stage encompasses the ecological crises and their consequences formed by the impacts of climate change. The effects and damages caused by climate change in the South Caucasus, including the territory of Azerbaijan, are particularly significant in this regard. In other words, while global warming manifests in mid-latitudes as rising temperatures, reduced precipitation, and an increased frequency of hazardous atmospheric phenomena, it is accompanied by rising sea levels in the world's oceans, territorial losses for small island states, and destructive monsoon-driven flooding in Southeast Asia (Taszarek et al., 2021; https://climate.nasa.gov/vital-signs/global-temperature/?intent=121).

The first and second stages of climate change formation exhibit similar characteristics at both local and global scales. This section will focus on the second stage (temperature anomalies) and the third stage (ecological crises) of climate change within the territory of the Republic of Azerbaijan. Azerbaijan, with its physical-geographical position in the South Caucasus, stands out from other regions and encompasses a vast area with complex orography. The region includes all the morphological units representing the South Caucasus as well as the influence of maritime factors (Museyibov, 1998).

Climate change in the country initially manifests through an increase in the average annual air temperature. According to historical data, the fluctuations in air temperature in the periods 1901-1930 (11.9°C), 1931-1960 (12.1°C), and 1961-1990 (12.2°C) are very small compared to previous base periods (30 years). However, compared to the 1961–1990 period, this indicator sharply increased by 0.8°C during 1991-2023 (Figure 1). Synoptic conditions play a significant role in this increase (Huseynov & Huseynov, 2022). The trend line shown in the graph is expressed by the formula y=0.0123x−11.741y = 0.0123x - 11.741. The statistical significance of the trend is represented by the following inequality (Safarov et al., 2024):

$$\frac{|R|}{\sigma_R} \geq t_{2\alpha}$$

There, σR represents the random standard quadratic error, and $t2\alpha$ is the two-tailed significance level. The quantile 2α, corresponding to a 97.5% two-tailed significance level, is calculated, and the values of $t_{2\alpha}$ are replaced with the predefined table values of the Student's criterion for different numbers of years. The random standard quadratic error (σR) is calculated using the following formula (Safarov et al., 2024):

$$\sigma_R = (1 - R^2)\sqrt{(n-1)}$$

There, n is the number of elements in the time series. At a significance level of 2a=0.05 (5%), $t_{2\alpha}$ has different values depending on the number of elements (n) in the time series. Calculations show that in the expression R^2=0.3257, the coefficient R is statistically significant. Additionally, based on the calculations, since the p-value is very small ($p<0.05$), the trend is statistically significant. This indicates that the observed increase in temperature values is not random.

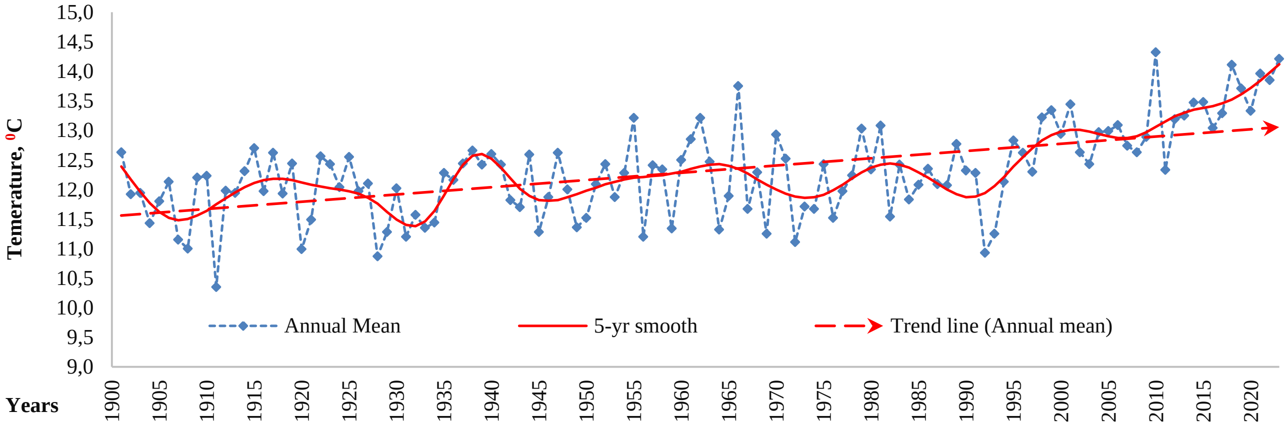

Figure 1. Dynamics of the average annual air temperature indicators in the territory of Azerbaijan (https://climateknowledgeportal.worldbank.org/country/azerbaijan/climate-data-historical)

Throughout the year, factors such as air masses affecting the country's territory, disruptions in surface cover, the albedo effect, the expansion of heat islands, and more are primary causes of the increase in air temperature. Throughout the year, southern cyclones entering Azerbaijan, Central Asian anticyclones, continental Arctic, maritime Arctic, "Azores high", tropical continental, and moderate latitude continental air masses change their initial meteorological characteristics, leading to significant changes in their trajectories (Voigt et al., 2021). In recent years, the inability of the Gulf Stream to reach northern Britain and its weakening in the Central Atlantic has occurred due to the impact of global warming (Ditlevsen & Ditlevsen, 2023). This directly indicates that in the region where the "Azores high" forms, the climatic impact of this current is being disrupted. Thus, as the Azores high has lost its initial conditions under the influence of global warming over the years, it distributes the "warming" effects to all regions. Other air masses have encountered such changes as well.

Winds are more frequent throughout the year in the Absheron Peninsula. This is due to the lack of large relief forms in the area. The majority of the recurring winds here are from the northwest (30%) and north (23%) directions. The intervention of winds from the southeast (10%) and south (16%) directions throughout the year is relatively high. The study of the impact of climate changes on wind patterns shows that, compared to the norm (1981-2010), there has been a change in wind directions between 2011 and 2023. Specifically, the recurrence of north winds decreased by 11%, while the recurrence of northwest winds increased by 15%. The difference for winds from other directions is minimal (1%) (Figure 2). The average speed of recurring winds throughout the year is 6.1 m/s. This indicator is 5-6 m/s in May, June, August, September, and October, and 6-7 m/s in the other months. The maximum wind speed in the Absheron Peninsula reaches 24 m/s throughout the year.

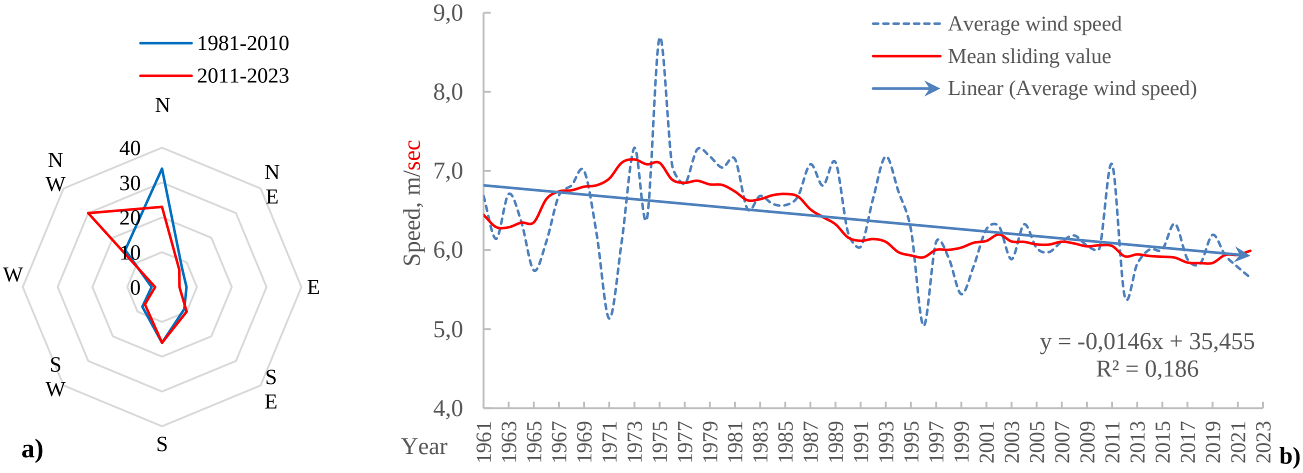

Figure 2. Interannual Variability of Mean Annual Wind Directions and Speeds in the Absheron Aquatory
(Source: National Hydrometeorological Service)

An analysis of the multi-year trend in average wind speed reveals that while wind velocity showed an increasing trend until 1973, a steady decline in mean annual wind speed has been observed since 1974. Although intermittent fluctuations occurred in certain years, the decreasing trend has become particularly persistent since 2000. This phenomenon results from reduced pressure differentials between regions caused by rising air temperatures.

The increase in solar radiation reaching the surface plays a significant role in the formation of climate change and the rise in global temperature. In Azerbaijan, the role of radiation balance disruption in the formation of climate changes is significant as well. Recently, changes have been observed in shortwave solar radiation and albedo levels. Areas with rising long-term temperature indicators have also indicated an increase in albedo levels (Huseynov & Huseynov, 2024). In the slopes of the Greater and Lesser Caucasus mountains, the increase in albedo is due to deforestation, glacier melting, snow cover reduction, and the degradation of natural vegetation on pastures. This process leads to increased absorption of heat by the surface (Trlica et al., 2017). The albedo effect influencing the increase in air temperature is associated with the expansion of deforestation in the Greater Caucasus, Lesser Caucasus, and Talish mountains. There, the rapid development of eco, rural, historical, architectural, and adrenaline tourism infrastructure accelerates deforestation. Deforestation leads to changes in the proportion of absorbed and reflected solar energy at the surface. Our research conducted using GIS technology shows that 12.8% of the country's area (11071 km²) is at risk of deforestation. This area includes 47.4% in the Greater Caucasus, 31.6% in the Lesser Caucasus, 17% in Lankaran, 3.1% in the Kura lowland, and 0.8% in the Nakhchivan region.

Moreover, the reduction in the area of snow and ice cover in the high-altitude regions of the Greater and Lesser Caucasus mountains, the drying of green landscapes transforming into semi-desert and dry-steppe regions, and the unsustainable use of pastures have contributed to the formation of the albedo effect. It is more appropriate to systematize the phased explanation of climate change through a comprehensive model. In this study, the first conceptual model of the climate change process in the territory of Azerbaijan was developed (Figure 3). A detailed explanation of all phases of this model is provided in the discussion of the study. In the model, interrelated, unidirectional, and sequential connections are represented by arrows.

The development of transportation, industry, and infrastructure in new large urban agglomerations accelerates atmospheric pollution. Additionally, the construction of residential, industrial, and transportation infrastructure has led to the disruption of the natural surface cover, the cutting of trees and shrubs, and the replacement of this cover with various layers of stone and asphalt. In such anthropogenic surfaces, albedo levels change, and an increase in air temperature is observed compared to the surrounding areas. Areas that release heat into the lower troposphere appear as small islands in thermal imaging from satellites, making the term "heat islands" more appropriate for these areas (Heaviside et al., 2017).

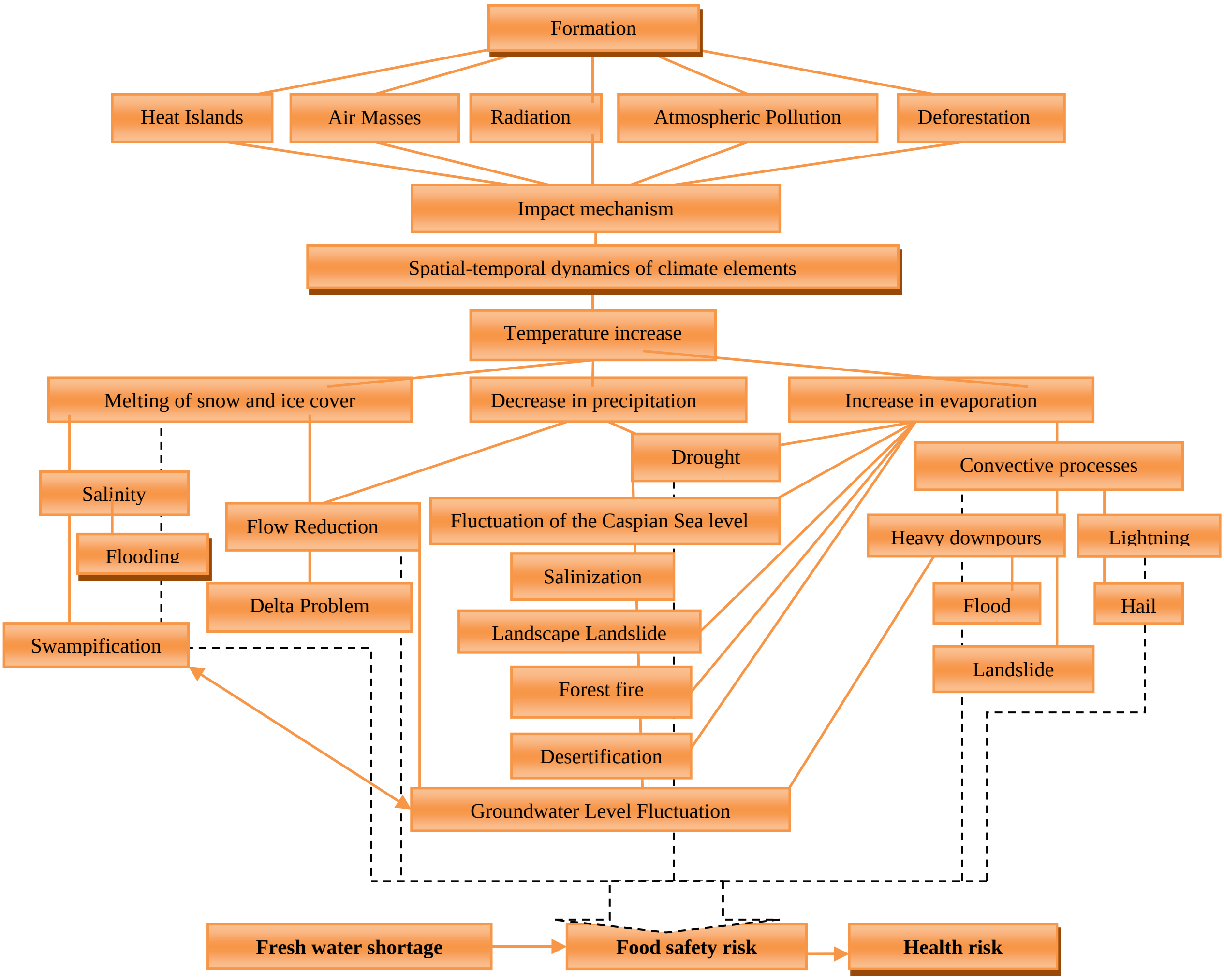

Figure 3. Conceptual Model of Climate Change in Azerbaijan

In Azerbaijan, heat islands cover an area of 3385.5 km² (3.9%). In the country, 31.4% of heat islands are located in the Lesser Caucasus, 27.3% in the Greater Caucasus, 26.1% in the Kura Depression, 5.1% in Lankaran, and 2.1% in Nakhchivan. Only 8.5% of the total heat islands are within the Baku agglomeration.During the post-Soviet period (after the 1990s), the development of industry and transportation accelerated the formation of agglomerations or large cities in the Republic of Azerbaijan. Cities such as Baku, Ganja, Nakhchivan, and others, where a significant portion of the population resides, serve as examples of such urban centers. Areas with high population density align with zones where employment opportunities have expanded, and large industrial facilities were located.

The increase in employment in these major cities has led to migration from other regions and accelerated urbanization. Efforts to improve the housing conditions of urban residents have triggered the rapid expansion of urban infrastructure.

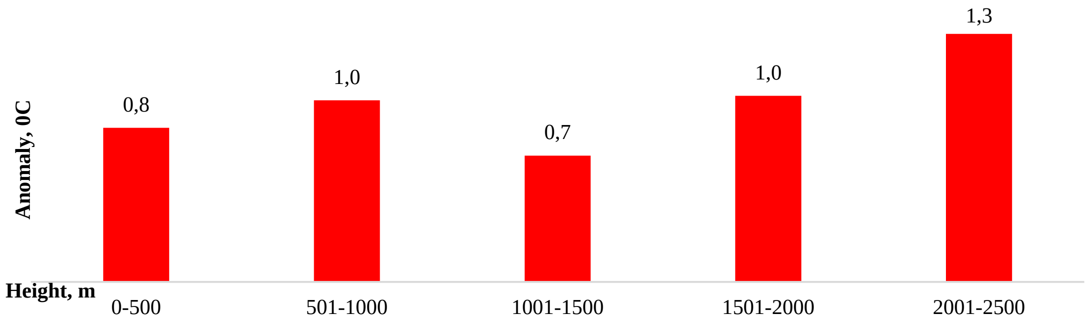

Figure 4. Air temperature anomaly by altitude across the territory of Azerbaijan (Source: National Hydrometeorological Service)

The largest urban agglomeration in Azerbaijan is Baku, home to one-fourth of the country's population. The expansion of the city's area has contributed to the formation of heat islands. As of January 1, 2023, Baku officially registered 2.34

million residents. The population density in the capital stands at 1,092 people per square kilometer. The rapid development of transportation and industry in Baku and other major cities has resulted in significant atmospheric pollution. Notably, the zones with the highest concentrations of atmospheric pollutants coincide with these urban areas. As in all regions, air temperatures in Azerbaijan have continued to rise sharply over the past 35 years. The temperature increases across elevations in the country, compared to the 1981-2010 period, during 2011-2023 is depicted in the figure below (Figure 4.

The air temperature increased by 0.8°C during the period 1991-2020 compared to 1961-1990 and by 0.9°C during 2011-2023 compared to 1981-2010. The increase in air temperature across Azerbaijan has led to the expansion of drought, a rise in potential evaporation, and a decrease in precipitation. The average annual temperature increase, ranging from 0.8°C to 1.3°C in various regions, has exhibited distinct characteristics (Huseynov, 2024). Across the country, air temperature increased by 0.9°C between 2011 and 2022. This rise was 0.9°C in winter, 1.1°C in spring, 1.2°C in summer, and 0.4°C in autumn. The highest increase, 1.6°C, was recorded in May and June. The rise in temperature significantly contributes to increased evaporation rates on the Earth's surface (Szilagyi et al., 2024). The highest levels of annual evaporation are observed on the surfaces of reservoirs, lakes, rivers, and bodies of water such as the Caspian Sea, Mingachevir, Sarsang, and Aras. The strong development of evaporation over the Caspian Sea's surface has resulted in an increase in water loss. Our research indicates that as a result of the fluctuations in the Caspian Sea level, 3,398 km² of saline coastal plains have formed, which constitutes 3.94% of the total country area. Half of these plains are newly emerged areas freed from sea water.

Evaporation has increased the demand for freshwater in the Kura Lowland natural region, one of the largest flat morphostructures in the country. Consequently, drought has expanded its area within the region. Over the past 33 years, the average annual air temperature in the Kura Lowland has risen from 15.0°C to 15.8°C, accelerating the degradation of forest shrubs, thickets, and riparian forests in mountainous areas. Not only has the Kura Lowland region experienced this effect, but all areas along the Aras River and mountainous terrains have been subjected to the "drought effects" of warming. The expansion of drought has been moving toward lower mountainous regions at elevations of 500-800 meters, affecting all mountainous regions Greater and Lesser Caucasus. This process has also been observed in the high mountainous areas of the Talish Mountains, particularly in river valleys and depression areas. The main result of the impacts of climate change in the territory of the Republic of Azerbaijan is the depletion of water resources and the increasing water scarcity over time. The results of our research are also confirmed by R. Ismayilov's studies (Ismayilov, 2024). The intensification of water scarcity leads to the development and expansion of all ecological crises. Balancing the growing demand for fresh water with responsible use can ensure a sustainable water strategy. The dynamics of surface and groundwater extraction have been analyzed in the study (Figure 5). Using state water usage accounting data (2000-2022), the volume of water extraction from water sources was analyzed by regions. Over the multi-year period (2000-2022), the amount of water extracted from surface water sources increased from 9.91 km³ to 13.03 km³. The maximum water extraction from the country's territory occurred in 2022, while the minimum was recorded in 2002. Overall, during this period, an average of 11.6 km³ of water was exploited from natural water sources. During this time, an increase of 2.2 km³ (11.4%) in the volume of extracted water was observed.

Recently, attention has also been paid to the dynamics of the volume of water extracted from groundwater sources in the country. Studies show that, between 2000 and 2022, there has been a significant increase in the volume of water extracted from groundwater sources. At the same time, during the average multi-year period, a decrease of 2.55 km³ in groundwater extraction was observed. The increase in groundwater extraction will lead to the depletion of water resources and the rapid development of water scarcity. Specifically, excessive water extraction from groundwater basins causes the depletion of these waters, land subsidence, damage to infrastructure and ecosystems, and the intrusion of saline water into freshwater layers in coastal areas. In addressing this issue, the application of sustainable practices in the effective management of water resources, continuous monitoring of groundwater levels, and regulation of extraction volumes is crucial. The analysis of water extraction by sources shows that the increase in the use of groundwater sources creates certain problems in the ecosystems of these areas.

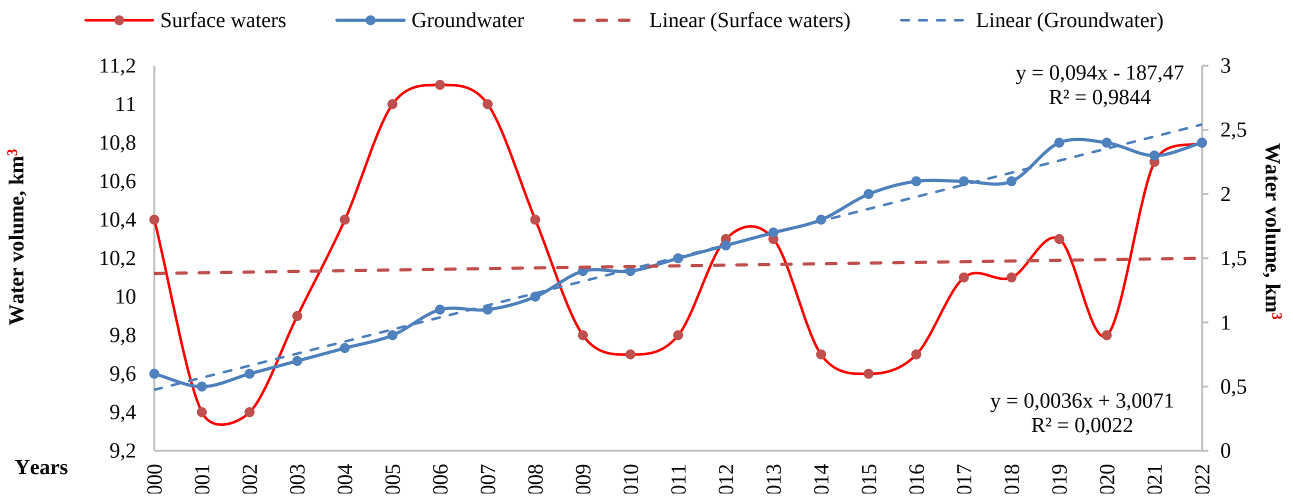

Figure 5. Long-term trends in average annual volume indicators of groundwater and surface water resources (Source: National Hydrometeorological Service)

Under the influence of modern warming, the increase in evaporation, along with the spread of drought, also impacts the atmospheric precipitation regime. In the country, the annual amount of precipitation has decreased by nearly 7% compared to the 1961-1990 period. This decline corresponds to approximately 26-31 mm. The negative anomaly of precipitation amounted to 4% (23 mm) in 2011-2023 compared to 1981-2010. The multi-annual precipitation amounts have decreased more significantly in 2011-2023 at elevations of 301-500 m and 1501-2500 m (Figure 6).

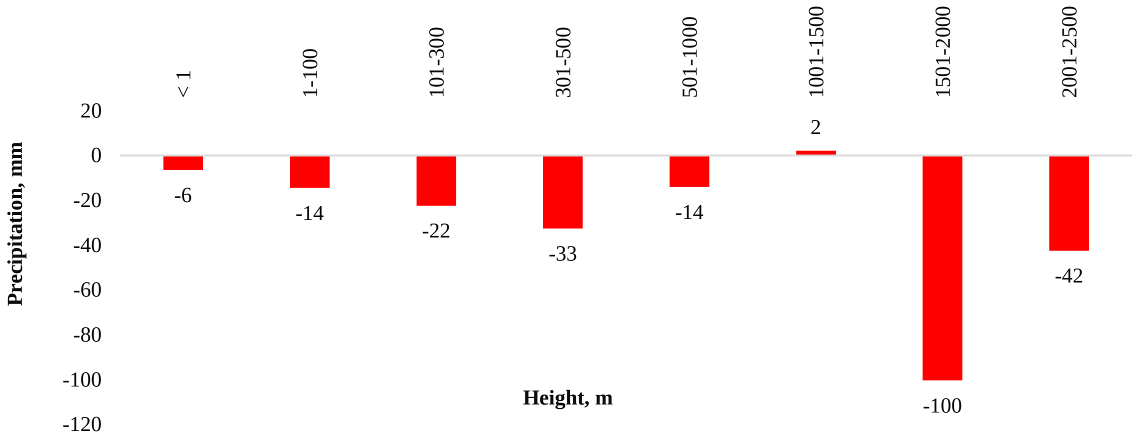

Figure 6. Anomaly of precipitation amounts by elevations in Azerbaijan (Source: National Hydrometeorological Service)

The influence of modern climate changes on the air masses that form the synoptic conditions in the territory of Azerbaijan has led to the alteration of their long-term characteristics, resulting in a decrease in precipitation. The reduction in atmospheric precipitation has created conditions for the expansion of drought and the upward shift of the lower boundaries of green landscapes to higher altitudes (Huseynov et al., 2024). Over time, shrubs are being replaced by semi-deserts and dry steppes, xerophytic forests by shrubs, and forests by forest-shrub complexes. This process is particularly evident on the southern slopes of the Lesser Caucasus Mountains. For instance, along the banks of the Hakari River, at altitudes of 900-1100 meters, the withering of forests and their replacement by forest-shrub complexes have been observed (Figure 7).

Figure 7. A dried forest massif in the altitude range of 900-1100 m in the southern part of the Lesser Caucasus region (The photo was taken on August 28, 2024, by Jamal Huseynov, on the right side of the Lachin-Minkend road in the Lachin district, at the 2nd kilometer of the road)

Although evaporation has increased across the country's surface, the amount of moisture contained within these air masses is significantly lower compared to previous years. This process is affecting the reduction of water resources in the region. In addition to the decrease in precipitation, shifts have also occurred in the periods of its occurrence throughout the year. Specifically, the period during which precipitation falls in solid form has decreased. Broadly speaking, if before the warming period, the snow cover on the southern slopes of the Greater Caucasus lasted from the end of December to mid-March, this period has now shortened to the beginning of January to the first ten days of March. Previously, this situation persisted in the southern part of the Lesser Caucasus from early November to late March, in the Talish Mountains from early November to the first ten days of April, and Nakhchivan from mid-December to early March.

Currently, this phase is observed with a reduction of at least ten days in both the start and end dates. The total number of days with snowfall has also decreased accordingly. Because the minimum temperature required for snowfall is recorded less frequently across the country's surface, and the effects of modern warming leading to 'milder' winters, precipitation during that period now tends to fall in mixed forms rather than as solid snow. Calculations show that, depending on the scenarios, the amount of potential evapotranspiration in the country's territory will increase by 15-35%. This change will lead to an increase in moisture deficit (climate-irrigation norm) by 70-540 mm.

Such a sharp rise in potential evapotranspiration will also worsen natural moisture conditions, causing the boundaries of moisture zones to shift toward the mountains (Aliev, 2021). A decrease in precipitation has led to an increase in the number of dry days in lowland and low-mountain areas. Additionally, the reduction in the period when precipitation falls in solid form and the increase in mixed precipitation poses a risk to the future existence of permanently and partially frozen areas. Alongside these effects, the impact of ablation on glaciers and snowfields in the high-altitude zones of the Greater and Lesser Caucasus Mountains during the warm season is also significant. In the study of glaciers, the research team first conducted field studies on the Tufan, Shahdagh, and Bazarduzu glaciers. Physical indicators obtained through GPS were integrated into the ArcGIS system, and their precise area measurements were determined.

The increase in the area and height of perennial glaciers, as well as their transition to firn, depends on the volume of solid precipitation from the previous year. The snow layer that remains unmelted into the next year (with a density of 50-300 kg/m³) is covered by new snowfall. Under the weight of the subsequent year's snow and partial melting, it begins to transform into firn (with a density of 400-830 kg/m³). In this way, perennial glaciers (with a density of 830-917 kg/m³) are formed (Roger, 2020). However, modern warming has accelerated the melting of snow on these mountain peaks, causing the area of glaciers and snowfields to shrink year by year. This trend is evident in the reduction of glaciers on the peaks of the Greater Caucasus-Bazarduzu (4466 m), Tufan Mountain (4191 m), and Shahdagh (4123 m)-which have decreased by 16-23% over the past 7 years, and the 'glacier tongue' has retreated upward by 80-100 meters. This indicates that the climate-snow line in mountainous regions has shifted from 2900-3000 m to 3000-3200 m in elevation. This process is clearly illustrated in the cartographic representation of the Tufan Mountain glacier's area dynamics over many years (Figure 8).

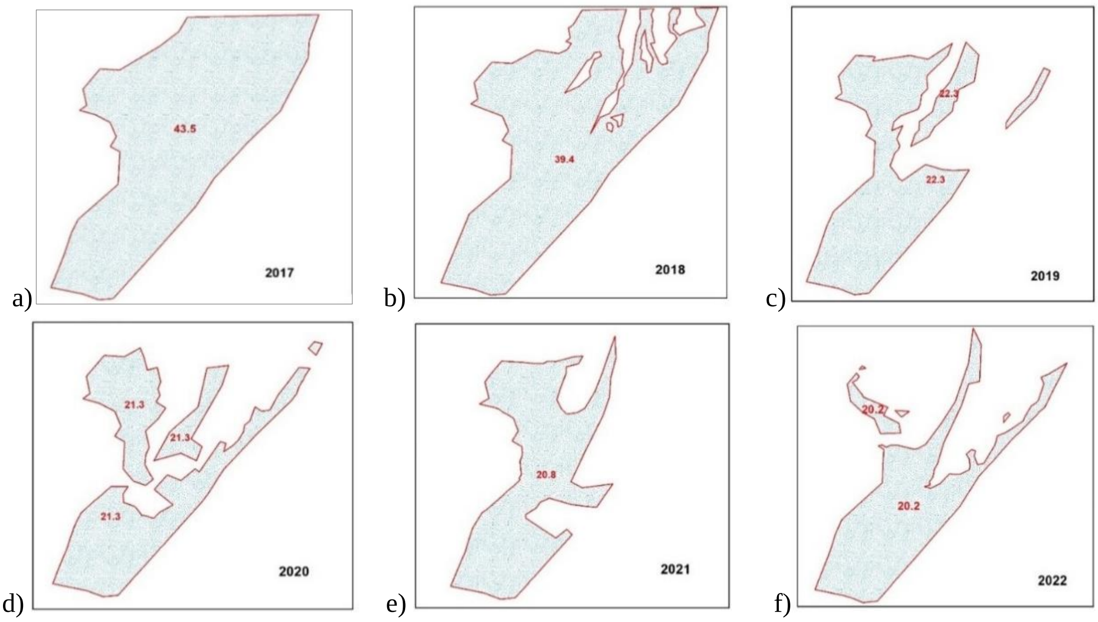

Figure 8. Long-term dynamics of the area of the Tufan Glacier (a-f)

In high mountain areas, the rapid melting of snow and ice cover in spring increases the flow volume of rivers fed by these areas over a short time frame. Such periods of high-water flow in rivers typically occur during transitional seasons, i.e., classical periods. However, in recent times, under the influence of climate change, sharp warming starting from early March has accelerated the melting of snow and ice cover. As a result, the flow volume of rivers during the traditional high-water period has increased by 1.5-2 times compared to previous periods. The rapid rise in water levels in rivers has led to the destruction of protective dams and the expansion of flooding zones (Arnell & Gosling, 2013).

Across the country, the annual runoff modulus increases with elevation. Under modern climate change conditions, in the Greater and Lesser Caucasus regions, the maximum annual water discharge in most high-water and flood-prone rivers has decreased, while winter minimum flows have increased (Imanov et al., 2009; 2024). Such events are frequently recorded in lowland areas around the Kura River, particularly in the Kura-Aras lowland. Flooding was observed almost every year over the past 15 years. The flooding that occurred in this zone in May 2010 is one of the most notable examples of significant hardship for the local population (Aghayev, 2018).

In the territory of Azerbaijan, alongside a decrease in the amount of atmospheric precipitation throughout the year, an increase in extreme precipitation events has also been observed. During the warm season, the increase in air temperature in lowland and low-mountain areas occurs due to intense insolation. Strong heating of the ground surface and maximum evaporation accelerate the development of convective processes in mid-mountain areas. Such synoptic conditions, along with torrential rains, create an environment conducive to the intense development of lightning and hail phenomena in cumulonimbus clouds. Under the influence of climate change, these processes have intensified and accelerated. In mountainous areas, the time phase for the development of cumulonimbus clouds has shortened. Sometimes, the majority of annual precipitation is recorded in the form of prolonged torrential rains. As an example, we can cite the intense torrential rains that occurred in Baku on November 14-17 and December 2-3, 2024. The persistence of torrential rains in mountainous regions poses a risk during transitional and warm periods of the year.

During transitional periods of the year, continuous rainfall occurs, increasing soil moisture levels. During subsequent intense rainfall, the infiltration of rainwater into the already saturated soil is delayed (Assouline, 2013). This creates rapid and abundant water flow on steep slopes. As a result, such flows quickly show the first signs of flooding in ravines. Widespread rainfall over a short period leads to the formation of powerful floods. Thus, floods formed in large rivers carry all the dissolved materials they encounter along their path. When this process has destructive force and water levels remain high for an extended period, it causes significant damage to transportation, tourism, and agricultural infrastructure, increases food security risks, and can result in human casualties. When such flood processes occur in summer, the excessively dry soil further delays infiltration, and rainfall with an intensity exceeding 20 minutes accelerates the formation of flood events.

The increase in the intensity of torrential rains triggers landslides in areas with steep mountain slopes, clayey soil layers, and large terrace massifs. This process is frequently observed on the steep slopes of the Greater and Lesser Caucasus Mountains. In recent years, Baku has also suffered from an increase in landslides. Over the past 35 years, the city has experienced a nearly 32% increase in precipitation, which has heightened landslide activity (Huseynov & Huseynov, 2022). On the Absheron Peninsula, where Baku is located, the rise in torrential rains, combined with the insufficient capacity of the planned collector systems for handling traditional maximum rainfall, delays the drainage of rainwater and leads to flooding in the city's low-lying infrastructure. One such flooding event on October 22, 2024, resulted in the loss of two lives.

The rise in temperature, decrease in precipitation, and melting of glaciers have led to a reduction in river flow. The decline in freshwater resources has also reduced the flow volume of the tributaries of the Kura and Aras rivers within Azerbaijan's territory. It should be noted that the Kura and Aras rivers pass through several reservoirs before entering Azerbaijan, where they experience stable flow (Imanov et al., 2024; Klaphake & Kramer, 2011). This flow further decreases within the country due to increased demand for irrigation and the impact of climate change on the rivers' tributaries (reduced flow, increased evaporation, etc.) (Abbasov & Flores, 2023). During the warm season, the water level in the Kura River delta decreases, allowing the salty waters of the Caspian Sea to penetrate inland. As a result, salinization expands further. In general, fluctuations in the Caspian Sea level are also linked to modern climate changes. The Volga River contributes 85% to the Caspian Sea's water balance, while the Kura, Terek, Sulak, and other rivers collectively account for only 5%. The increase in temperature in the basins of these major rivers has affected climatic elements, reducing their flow volume. Additionally, the increase in evaporation from the sea surface has played a decisive role, causing the sea level to drop to -28 meters (Safarov et al., 2024). As the Caspian Sea recedes, the area of salt flats freed from salty waters continues to expand. During this process, intense insolation breaks down the salty sand, and aeolian processes carry salt particles inland. This primarily results in the expansion of salinization in the Kura-Aras lowland and inland areas. Moreover, during the high-water period, the water level rises in the areas through which the Kura and Aras rivers flow. Flooding processes, occurring along the riverbanks at elevations up to 100 meters above sea level, raise groundwater levels and create temporary wetlands.

In recent years, the anomalous rise in temperature during certain months has further intensified evaporation during transitional periods of the year. This has also expanded the development of convective processes from early spring to mid-summer. As a result of these processes, torrential rains, hail, and lightning are observed. Hail and lightning phenomena are more frequently recorded in mountainous areas. Due to the spatiotemporal shifts of these processes, the risk of hazards has increased in mountainous regions. The majority of areas (47.3%) where convective processes (lightning, hail) are expected to expand are located in the Lesser Caucasus region, covering an area of 14,877 km² (17.2% of the country). In the Greater Caucasus region, 37% of the area (11,632 km²) prone to such hazardous atmospheric processes is located, representing approximately 13.5% of the country's surface. Additionally, 8.5% of this area (2,659 km²) is located in the Nakhchivan region, accounting for 3.1% of the country. The zones experiencing hail cover 8.5% (2,291 km²) of the Lankaran region, representing 2.7% of the country's total surface area. In recent years, the rapid formation phase of convective processes is completed in the first half of the day. Lightning and hail processes form in mountainous areas during the early afternoon hours. The recurrence of lightning and hail events has increased significantly in recent years. These atmospheric phenomena cause considerable damage to agriculture, industry, and transportation. Shifts in the recurrence of such processes are also becoming evident. Lightning and hail events are primarily recorded in the mid-mountainous areas of the republic. Lightning events are more frequently observed in the mid-mountainous regions of the Greater and Lesser Caucasus Mountains and the Absheron Peninsula, while hail is more persistent in mid-mountainous areas. The calculations indicate that 36.5% of the country's surface is at risk of being affected by hazardous atmospheric processes.

Research on the impacts of regional climate change on hazardous atmospheric processes, including hail, is of particular importance. This is because hail causes significant damage to agriculture and infrastructure. For this reason, the analysis of increasing observational data over the years also allows us to identify trends in hail events from 1979 to 2020.

Doppler radar uses radar reflectivity (Z) and other parameters to detect the characteristics of hail particles (Jun et al., 2021). During hail events, radar reflectivity is very high (typically $Z > 55\ dBZ$). $Z=\int \sigma D^6 n(D)dD$

There, σ represents the radar cross-section, D is the diameter of the particles, and $n(D)$ is the particle size distribution. In the country’s territory, hail processes are most frequently recorded on the northeastern slopes of the Lesser Caucasus

Mountains. Analysis of hail events in this area shows that the increase in hail recurrence is more pronounced in lowland areas. However, this indicator has also risen significantly at stations located in mid-mountainous regions. The increase in hail events is most notable in May, June, and July. In other months, hail recurrence has undergone minor changes (Table 1).

Table 1. Anomalies in hail events from 1991 to 2020, % (Source: National Hydrometeorological Service)

Station	**Month**									**Year**
	II	III	IV	V	VI	VII	VIII	IX	X	
Gadabay	0	2	4	2	8	7	-1	6	1	29
Dashkasan	0	0	2	19	19	7	7	9	2	64
Shamkir	-3	3	3	3	10	3	3	-3	3	27
Goygol	0	0	3	-7	13	13	-13	0	3	13

In the research, advanced GIS (Geographic Information System) technologies were used to identify areas affected by climate change and regions at risk of ecological crises. After refining the elevation ranges obtained from mathematical calculations using DEM (Digital Elevation Model) files, their areas were determined. A comprehensive map was developed to predict the spread of hazardous ecological crises and the impacts of climate change in the future. The delineation of ecological crisis zones was carried out through the following GIS steps (Figure 9).

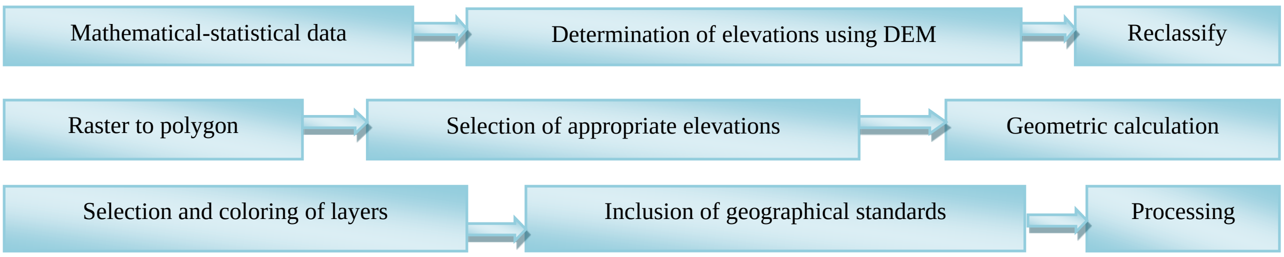

Figure 9. Methodology of the research conducted in GIS

A map was developed to provide a general overview of ecological concerns and processes that have reached crisis levels due to climate change (Figure 10). Natural causes have contributed to the current expansion of ecological crises.

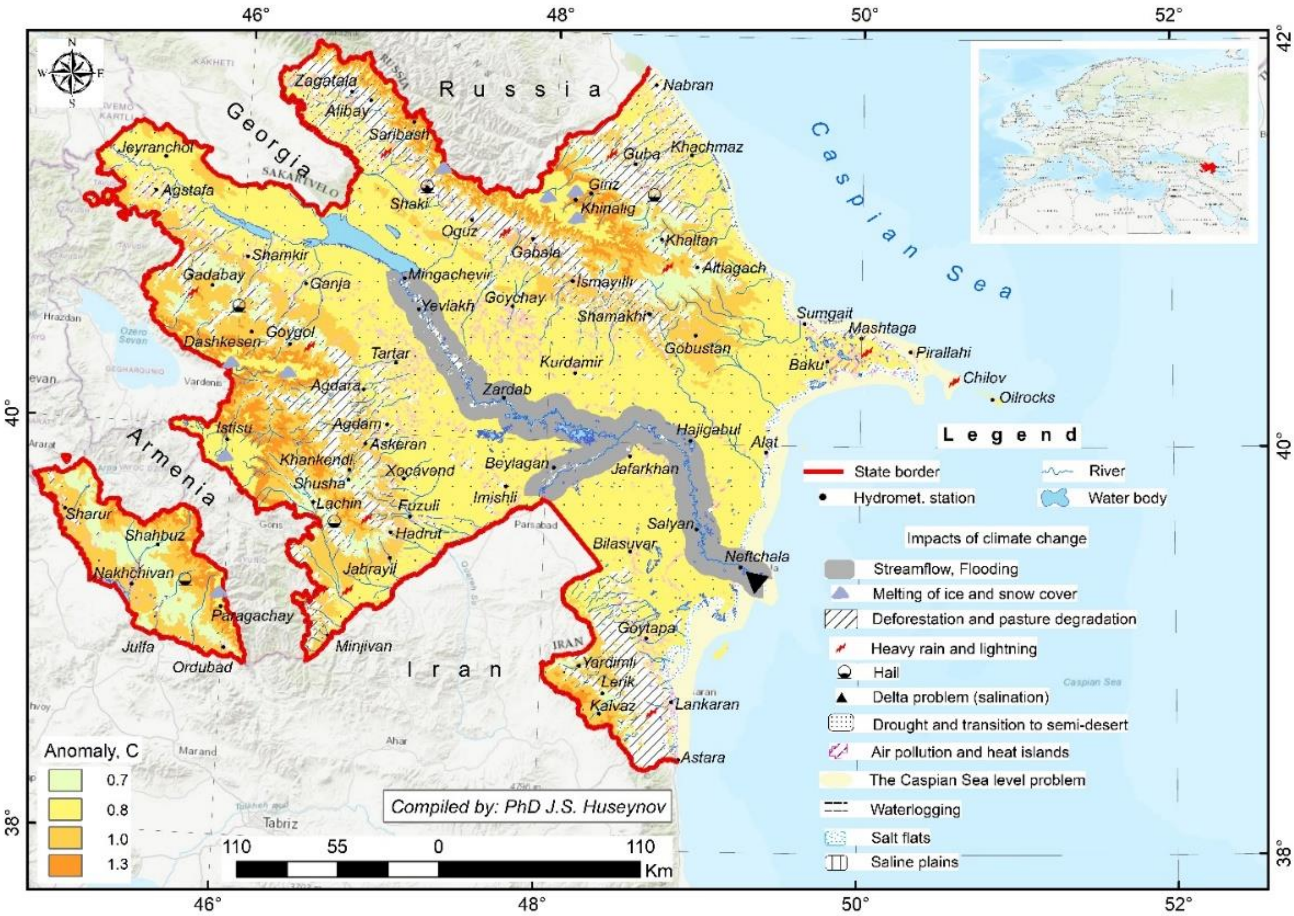

Figure 10. Map of ecological problems caused by climate change in the territory of the Republic of Azerbaijan (Source: National Hydrometeorological Service)

However, the sharp spatiotemporal expansion of destructive natural events such as waterlogging, salinization, hail, lightning, etc., has occurred over the past 3 and half decades. Areas where such processes are currently developing or are likely to expand in the future are reflected on the map.

CONCLUSION

The analysis of hazardous climatic factors in Azerbaijan from 1900 to 2023, along with the conceptual model developed based on these analyses, has enabled a precise identification of climate change issues and yielded the following comprehensive findings:

1. The ecological impact mechanism was systematized with the model that determines the effects of climate change. According to the model, compared to the norm (1981-2010), after an increase of 0.9°C in air temperature between 2011 and 2022, the main effects of climate change are the increase in evaporation, changes in wind directions and speeds, and a decrease in precipitation (by 4%).
2. The increase in air temperature has accelerated glacier melt (15-23% reduction over the past seven years), leading to increased exploitation of groundwater resources, reduction of surface water reserves, more frequent droughts, and expansion of desertification.
3. The increase in evaporation, reduction of glaciers, and decrease in precipitation have caused a decline in the current water level of the Caspian Sea. As a result, saline plains have formed across 3,398 km² of land (3.94% of the country's territory). Climate change has also expanded the spatiotemporal range (by 36.5%) of droughts, salinization, lightning, hail, landslides, and torrential rains in Azerbaijan.
4. The conceptual model for assessing climate change impacts will support the systematic planning of future research, development of advanced new models, and achievement of significant results in combating climate change.

The crises caused by observed climate changes in the territory of the Republic of Azerbaijan continue to expand gradually. The country's efforts in combating climate change at both international and local levels in recent years aim to mitigate these crises. While serious steps are being taken to limit global temperature rise to 1.5°C, these measures are insufficient to prevent freshwater shortages. Communities in the mountainous regions of the country are increasingly suffering from the acceleration of natural disasters. These processes are contributing to a rapid increase in risks to food security.

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