



Pashayev, Nariman ^{1*} – Aghayev, Ziyafat ² – Maharramova, Khatira ³

Hail Events in Azerbaijan: Geographical Assessment and Socio-Economic Impacts on Agriculture and Settlements

ABSTRACT

Observations of hail events in the Republic of Azerbaijan from 2020 to 2025 highlight their significance as a risk factor for agriculture and socio-economic life. A total of 343 events were recorded, with a sharp increase in 2023–2024 (101 and 107 events), marking the peak period of hail. Annual dynamics were analyzed alongside hailstone size: small (≤ 1 mm) and medium (1–10 mm) hailstones were most common, causing local to moderate agricultural damage, while large (11–20 mm) and very large (>20 mm) hailstones, though rare, had severe impacts. Regional distribution shows high-risk zones in Gazakh-Tovuz, Ganja-Dashkasan, and Shaki-Zagatala, medium-risk zones in Karabakh, Mountainous Shirvan, Guba-Khachmaz, and East Zangezur, and relatively safe zones in plains and coastal areas. The higher incidence in mountainous areas is linked to geographic and meteorological conditions. To mitigate risks, state-level measures, including radar and warning systems, insurance expansion, and modern technologies, are recommended.

Keywords: hail events, geographical distribution, hailstone sizes, socio-economic impacts, meteorological observations.

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¹ DSc (Geography), Head of Laboratory of Geopolitics and Economic Geography, Institute of Geography, Baku, Azerbaijan, (Corresponding author). Email: pashayevnariman1960@gmail.com, Tel: +994 050 347 36 70.

² PhD (Geography), Senior Researcher at the Laboratory of Land Hydrology, Institute of Geography, Baku, Azerbaijan. Email: kreativagayev@gmail.com

³ PhD (Geography), Associate Professor of the Department of “Public Management and Social Innovations” at the Azerbaijan State University of Economics (Unec). Email: xatira.maharramova65@gmail.com

INTRODUCTION

Even though hail is a characteristic phenomenon in mountainous and foothill areas worldwide, the damage it causes to people's lives and economic activities, as well as the social and ecological problems it generates, cannot be avoided. According to the International Meteorological Organization, the damage caused by hail to agriculture alone amounts to 6 billion US dollars annually. The Republic of Azerbaijan, as part of the world's mountainous countries, is one of the most exposed areas to hail in the South Caucasus due to its unique physical-geographical conditions and geographical location (Babakhanov & Pashayev, 2004). Consequently, the economy of the Republic suffers an average annual damage of 9–10 million US dollars. Hailstorms cause serious harm to agriculture, and powerful events often lead to severe damage to flora and fauna, vehicles, social infrastructure, residential and other building roofs, livestock, electricity and communication lines, as well as state and local communication networks. Intensive hailstorms are frequently accompanied by strong lightning and tornadoes with speeds exceeding 20–30 m per second.

Although hailstorms generally affect local areas compared to other natural disasters in the Republic, their intensity and scale can sometimes result in substantial material and ecological damage. While hailstorms are natural processes determined by physical factors such as occurrence, recurrence, and spread, their consequences are primarily socio-economic due to the damage inflicted on human life and economic activity. For this reason, the study of hailstorms as a complex problem from economic and geographical perspectives is of great scientific relevance (Kunz et al., 2025). Examining hailstorms, which are primarily characteristic of mountainous and foothill regions, from an economic and geographical standpoint reveals that, despite certain similarities, notable regional differences exist. Studying the regional characteristics of hailstorms in the Republic, depending on the location of farms, and identifying the areas where they occur most frequently, is crucial for predicting these events and for the territorial organization of production. Several methods are used worldwide to combat hail (Abshaev, 2000). The most widely applied methods include:

- Cloud seeding – a technique used to alter the formation of hailstones. Chemicals, usually silver iodide or sodium chloride, are sprayed into clouds to turn water droplets into small frozen crystals, causing them to fall as small raindrops and preventing the formation of large hailstones (Safarov, 2009; 2012).
- Hail shelters and protective nets – especially used in horticulture and viticulture. Nets or special covers protect plants from hail. This method is natural and flexible, but effective only in certain areas (Wieringa & Holleman, 2006).
- Radar and warning systems – meteorological radars track hail clouds, providing timely warnings to farmers and urban infrastructures. This is one of the most important steps to reduce damage, allowing people to move vehicles to shelters or postpone work (Kim et al., 2023).

Some countries attempt to disperse hail clouds by launching hail rockets or using sound and electrical discharge methods, although these are less common. Additionally, field planning and sustainable

agricultural practices—such as adjusting planting periods and selecting appropriate plant species—help protect crops most vulnerable to hail damage.

METHODS

The study is based on instructions from the *State Programs for the Socio-Economic Development of the Regions of the Republic of Azerbaijan*, materials from the State Statistical Committee of the Republic of Azerbaijan, the Ministry of Emergency Situations, and the Ministry of Ecology and Natural Resources, as well as systematic research and practical recommendations on hail phenomena conducted by scientists in the CIS and other countries. In particular, statistics from 54 hydrometeorological observation centers were utilized.

The research employs comparative, statistical, mathematical, and systematic methods to analyze hail events. Comparative analysis identifies spatial and temporal differences in hail occurrence, while statistical methods evaluate the frequency, variability, and trends of these events. Mathematical analysis enables the calculation of recurrence and intensity indicators. A systematic approach ensures an integrated and coherent interpretation of results within a unified analytical framework.

Independent variables in this study include geographical location (economic regions), altitude, and specific observation years from 2020 to 2025. These factors are used to analyze dependent variables, which comprise the total frequency of hail events, hailstone size, and economic damage to agriculture and infrastructure. By applying statistical and mathematical methods to these variables, the study establishes the relationship between mountainous terrain and the peak periods of climate risk observed in 2023–2024.

RESULTS

Physical and Orographic Conditions of Hail Formation

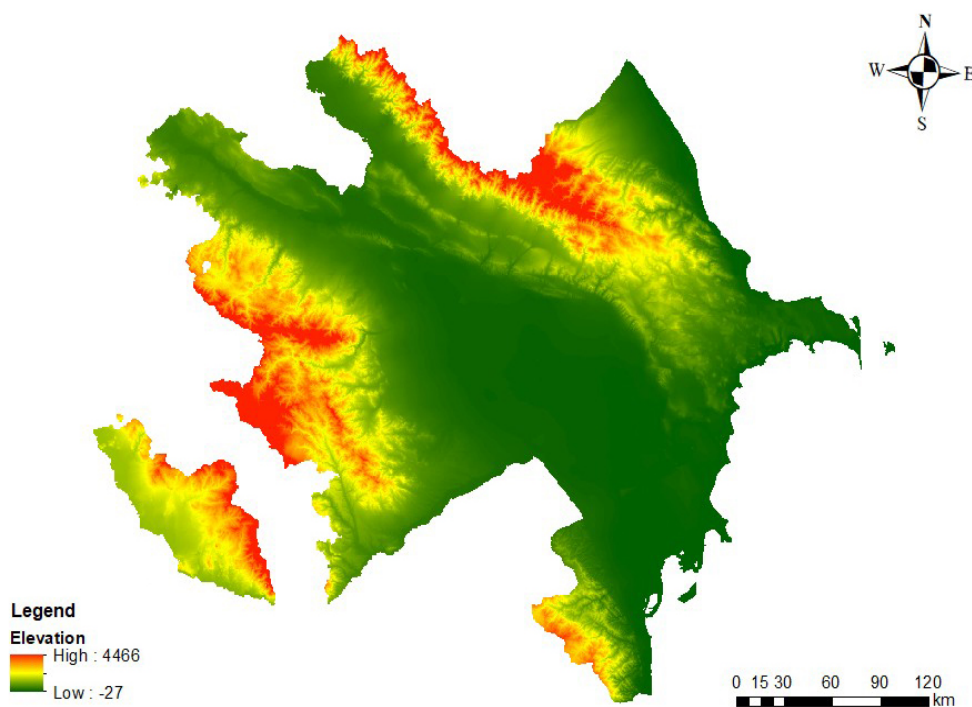
Hail, an atmospheric precipitation consisting of spherical particles and irregular ice crystals, typically forms from cumulonimbus clouds. Hail clouds primarily develop during the warm season on cold atmospheric fronts, and rarely are they associated with internal processes; they generally do not form on warm fronts. Hail grains can be conical, pear-shaped, ellipsoidal, or irregular, with densities ranging from 0.6 to 0.9 g/cm³ depending on formation conditions.

Several factors play a major role in hail formation: predominantly mountainous terrain, high vertical development of clouds, intense convection, cold fronts with high-speed air masses, and very low temperatures in the upper cloud layers. Hail cloud velocities range from 15–20 m/s, occasionally reaching 20–30 m/s. High humidity within the clouds is required for hail formation. Hailstones typically measure 5–50 mm in diameter, sometimes larger, causing significant damage to agriculture. Strong hailstorms are often accompanied by wind gusts reaching up to 40 m/s, which further amplify

damage. Hail, sometimes accompanied by heavy torrential rains and frequent lightning, can cover areas up to 10 km wide and tens or even hundreds of kilometers long (Mutallibov, 1964).

This has resulted in an uneven distribution of hailstorms in Azerbaijan (Shikhlinsky, 1949; Madatzadeh, 1957; Amiranashvili et al., 2019). In the Greater Caucasus, the northeastern and southern slopes differ in both frequency and intensity of hailstorms. The northeastern slope, being closer to the sea, experiences relatively unfavorable conditions for hail cloud formation, whereas convective flows on the southern slope are stronger, promoting more frequent hailstorms.

Figure 1. Elevation Map of Azerbaijan



Altitudinal and Regional Distribution

Based on the digital elevation model of Azerbaijan (Figure 1), altitudes in the country range from –27 meters to 4466 meters. Higher-altitude areas include the Greater Caucasus, Lesser Caucasus, and the mountainous regions of Nakhchivan.

In the Greater Caucasus, hail is generally observed once per year in high-mountain areas and twice per year in low-mountain areas. At elevations of 1000–2000 m, hail recurrence increases by approximately 0.4 days per 100 m. In the high-mountain zone (2300–2700 m), annual recurrence reaches 7–8 days. On the northeastern slope, hail is most frequent at 2200–2400 m, with 3–4 days of occurrence annually.

Hail is more frequent in the Lesser Caucasus than in the Greater Caucasus, with differences between the northern and southern slopes. In the northern foothills, hail occurs about once per year, while in middle-mountain areas it occurs three times per year. The highest frequency is observed at

2300–2700 m. On the northern slope, hail occurs 9–11 days per year, and on the southern slope, 7–8 days at altitudes of 2400–2900 m.

In the Nakhchivan Autonomous Republic, the highest hail frequency occurs at 2800–3200 m, amounting to 5–6 days per year. Around the Talysh Mountains, unfavorable conditions for hail cloud formation result in hail only 2 days per year at 1000–1200 m; above 1200 m, hail is rare. In coastal areas and the Kura-Araz lowland, hail occurs once every 2–3 years.

Seasonally, 60% of hail in plains occurs in April–May, while in mountainous areas, 60–70% falls in May–June. A secondary peak is observed in September–October. Overall, hail is most frequent in May–June across Azerbaijan. In Nakhchivan, intensive hail occurs in April and May due to the bareness of mountain ranges, valleys, and slopes (Pashayev, 2018).

Recurrence and Spatial Distribution (2020–2025)

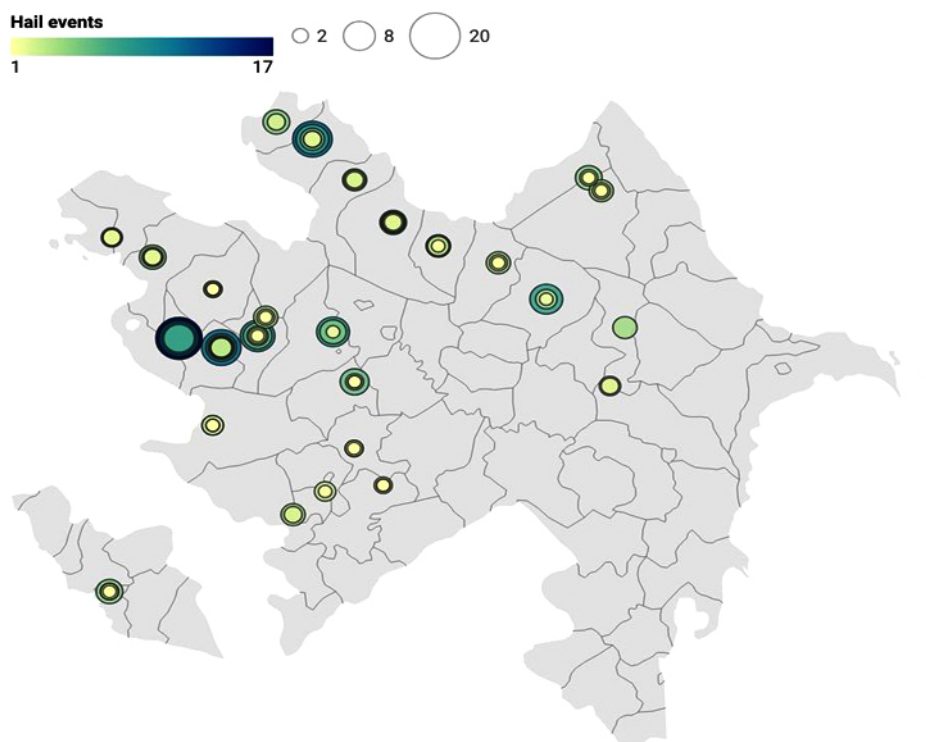
In recent years, due to changes in individual climate components, it is of great interest to study the characteristics of hail distribution across Azerbaijan under newly emerging conditions and to determine recurrence trends. Data reflecting the economic impact of hail events can be consistently studied using records compiled by the State Insurance Department (1960–1995), annual materials published by the Hydrometeorology Committee (from 1966), the National Hydrometeorology Department of the Ministry of Ecology and Natural Resources (2000–present), and reports from the Ministry of Emergency Situations Commissions (2006–present). Using these sources and personal observations, we examined the damage caused by hail to Azerbaijan's economic structure. Analysis of the past six years indicates that hailstorms are comparable to other natural disasters in terms of the damage inflicted on the Republic's agricultural sectors. Analysis of materials from the National Hydrometeorology Department for 2010–2024 demonstrates that hail recurrence and damage indicators vary significantly among different regions and districts of Azerbaijan.

In Figure 2, the size of the circles represents the number of hail events, while the color gradient indicates the relative intensity; larger and darker circles correspond to higher recurrence. Observations show that hail events are concentrated mainly in the western and northwestern regions, where both frequency and intensity are higher than elsewhere. In central and eastern regions, hail is rarer and more localized. Southern regions and the Nakhchivan Autonomous Republic exhibit relatively low recurrence rates. Overall, the map highlights uneven spatial distribution of hail events, with higher risk in specific geographic zones. These findings correspond closely with the elevation map in Figure 1, suggesting a strong association between hail occurrence and orographic features.

The annual recurrence of hail events in Azerbaijan (2020–2025) is summarized in the list below (Ministry of Ecology and Natural Resources, 2025). A total of 343 hail events were recorded: 29 in 2020, 35 in 2021, 26 in 2022, 101 in 2023, 107 in 2024, and 45 in 2025. A sharp increase occurred in 2023 and 2024, with 3–4 times more events than in previous years. In 2025, the number of events decreased but remained higher than in 2020–2022. Each hail size group is analyzed as follows:

- Hail ≤ 1 mm: These represent the smallest hail events, generally weak and causing minimal agricultural damage. Examples include 1.1 mm in Zardab (2020), 0.8 mm in Gazakh (2021), and 0.5 mm in Zagatala (2024).
- Hail 1–5 mm: Small hail events, more widespread, causing some agricultural damage. Recorded events include 5 mm in Ismayilli and Aghstafa (2021) and 3–4 mm in Shamakhi, Gabala, and Shaki (2024).
- Hail 6–10 mm: Medium-sized hail, affecting larger areas and causing significant agricultural damage. Examples: 6 mm in Nakhchivan (2021), 10 mm in Goygol (2022), and 8–10 mm in Zagatala (2023–2024).
- Hail 11–15 mm: Large hail, causing serious damage to agriculture and infrastructure. Recorded events include 13 mm in Goygol (2020), 12–15 mm in Shaki (2021), and 12–15 mm in Khojaly (2024).
- Hail 15–20 mm: Large-grained hail causing major damage to agriculture and settlements, e.g., 16 mm in Dashkasan (2020), 25 mm in Dashkasan (2021), 16 mm in Dashkasan (2022).
- Hail >20 mm: Very large hail, extremely destructive. Examples: 20–25 mm in Yardimli (2023), 25–30 mm in Gabala (2023), 30–35 mm in Aghdam (2023).

Figure 2. Areas Prone to Hail in Azerbaijan and Their Relief Features



Source: Compiled based on data from the Hydrometeorology Department of the Ministry of Ecology and Natural Resources (2020–2025).

Regions with the highest number of hail events include Gadabay (73 events), Dashkasan (34), Zagatala (28), Goygol (21), Shaki (17), Goranboy (14), Tovuz, Oghuz, Nakhchivan, and Ismayilli (12 each). Gadabay and Dashkesan, in particular, are the most hail-prone areas due to their mountainous geography.

Moderate hail occurrence is observed in Gakh and Gazakh (9 events each); Shamkir, Kalbajar, and Gusar (8 each); Balakan, Gabala, Ganja, and Guba (7 each); Lachin (6); and Gobustan, Aghdam, Shusha, Khojavend, and Shamakhi (4–5 each). In these regions, hail events are local but recur at stable or moderate levels annually. By year, the regional distribution shows:

- 2020: Gadabay and Dashkasan (7 events each)
- 2021: Gadabay (9 events), Zagatala, Dashkasan, Nakhchivan (2–4 events)
- 2022: Gadabay (12 events) and other regions
- 2023: Gadabay (17), Zagatala (8), Goranboy (8), Goygol (6) – peak year
- 2024: Gadabay (16), Dashkasan (12), Zagatala (12), Goygol (9), Ismayilli (8) – high recurrence
- 2025: Gadabay (12), Zagatala (4), Gakh (3), Tovuz (5) – decrease, but Gadabay remains highest (Table 1).

Table 1. Risk Distribution by Zones

Risk zones	Areas
The riskiest zones	Include Gadabay, Dashkasan, Zagatala, Goygol, and Shaki, where hail events are frequent and frequent
The medium-risk zones	Include the regions of Gakh, Gazakh, Shamkir, Kalbajar, and Gusar, where the recurrence of hail events is moderate
Relatively safe zones	Include the Shamakhi, Aghdam, Shusha, Khojavend, and Gobustan regions, and hail events are rare and local in nature

Analysis of hail event recurrence in the economic regions of Azerbaijan (2020–2025) indicates that hail will continue to affect the Absheron–Khizi region and has impacted nearly all areas of the country, with the exception of the Baku region. In the Gazakh–Tovuz region, a total of 102 hail events were recorded: Gadabay accounted for 73, Gazakh for 9, Tovuz for 12, and Shamkir for 8, making this zone the highest in overall frequency. The Shaki–Zagatala economic region ranked second with 80 hailstorms: 28 in Zagatala, 17 in Shaki, 12 in Oghuz, 9 in Gakh, 7 in Balakan, and 7 in Gabala. The Ganja–Dashkasan economic region ranked third with a total of 62 hailstorms, including 34 in Dashkasan, 21 in Goygol, and 7 in Ganja. The Karabakh economic region ranked fourth with 25 occurrences, with Tartar recording 10, Agdam 5, Khojavend and Shusha 4 each, and Khojaly 2. Other regions recorded fewer events: 21 hailstorms in mountainous Shirvan, 15 in Guba–Khachmaz, 14 in the East Zangezur economic region (8 in Kalbajar and 6 in Lachin), 12 in the Nakhchivan economic region, and 5–6 in each of Central Aran, Mil–Mughan, and Shirvan–Salyan. Based on these data, the recurrence of hailstorms allows the division of regions according to risk levels.

Our analyses indicate a sharp increase in the frequency of hail events in 2023 and 2024, which represent the peak period of climate risk. Although the number of hail events decreased in 2025, this process persisted in high-risk regions. The recurrence of hail was notably higher in mountainous areas and lower in regions with plains and a subtropical climate. The impact of hail on different regions of the Republic demonstrates that it creates significant problems both locally and regionally. Among the economic regions, the Gazakh–Tovuz and Ganja–Dashkasan areas are particularly affected (Table 2).

Table 2. Risk Distribution by Economic Regions

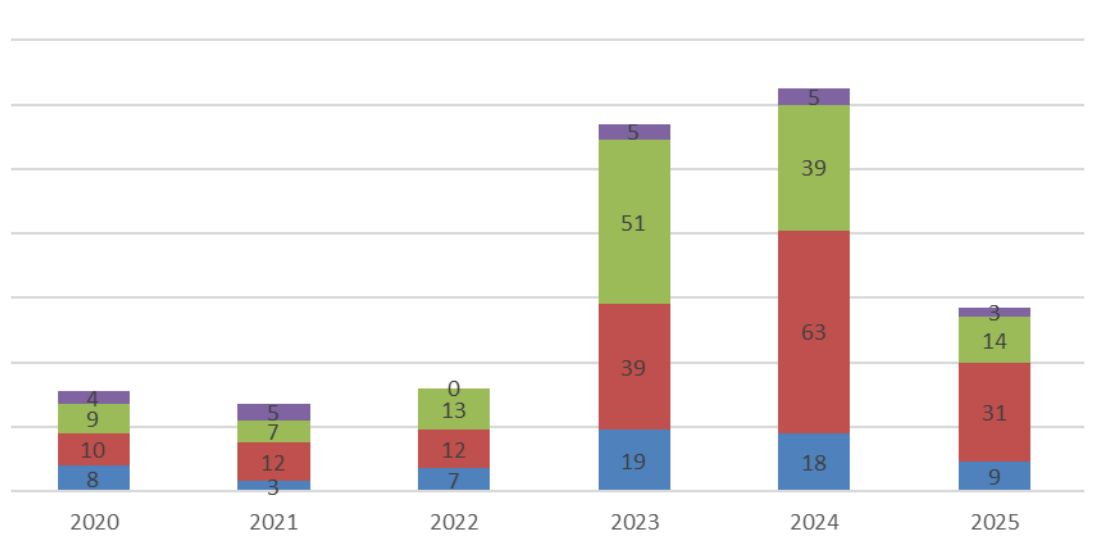
Risk levels	Economic regions
The riskiest economic regions	Gazakh-Tovuz (102 cases, especially Gadabay district – 73 cases)
High-risk regions	Shaki-Zagatala (80 cases), Ganja-Dashkasan (62 cases)
Medium-risk regions	Karabakh (25 cases), Mountainous Shirvan (21 cases), Guba-Khachmaz (15 cases), Eastern Zangezur (14 cases)
Relatively safe regions	Absheron-Khizi, Baku, Lankaran-Astara, Central Aran, Mil-Mughan, Shirvan-Salyan – incidents are few and local in nature

Hail Size Grouping and European Context

Figure 3 shows the analysis of hail events in Azerbaijan by diameter (2020–2025) as follows:

- Hail ≤ 1 mm: The smallest hail events, observed with weak intensity, causing minimal agricultural damage. A total of 64 events were recorded, with the highest recurrence in 2023 and 2024 (19 and 18 events, respectively). These events are local and mainly occur in spring and early summer.
- Small hail (1–10 mm): More widespread events causing moderate damage to agriculture. A total of 167 events were recorded, with the highest number in 2024 (63 events). Hailstones of this size particularly affect vegetable and fruit crops.
- Large hail (11–20 mm): These events cause significant damage to agriculture and infrastructure. A total of 133 events were recorded, peaking in 2023 (51 events). Hailstones of this size can destroy crops and damage buildings and vehicles.
- Very large hail (>20 mm): The largest and most destructive events. A total of 22 events occurred, with the highest numbers in 2021, 2023, and 2024 (5 events each). Though rare, these events have the strongest destructive impact.

Figure 3. Hailfall Grouping by Diameter (2020–2025)



Source: Compiled based on data from the Hydrometeorology Department of the Ministry of Ecology and Natural Resources (2020–2025).

Overall, Figure 3 highlights hail events in Azerbaijan were relatively few in 2020–2022, sharply increased in 2023–2024, and decreased in 2025. While small-diameter hail (1–10 mm) is the most common, the largest hailstones (11–20 mm and >20 mm) cause the greatest damage.

In 2023, Europe also experienced record hail activity. According to the European Severe Weather Database, 9,627 large hail reports were recorded, including 1,931 very large (≥ 5 cm) and 92 giant (≥ 10 cm) hail events. France, Italy, and Germany reported the most events, while the most destructive hail occurred in Italy, including a 19 cm diameter hailstone in July, injuring hundreds and causing billions of dollars in agricultural and infrastructural damage (European Severe Storms Laboratory, 2024).

Historically, Azerbaijan has primarily relied on rudimentary methods to combat hail. Therefore, in regions with active hail formation, consistent state-level measures are necessary (Ayyubov & Rahimov, 2000). The Cabinet of Ministers should allocate annual funds to prevent hail damage, and these measures should be considered in regional budgets.

The development of a comprehensive hail mitigation network in Azerbaijan is a priority. International studies emphasize the physics of hail formation and methods to actively influence hail processes (Ismailov, 2014). Theoretical and experimental research in cloud physics has led to effective methods for artificial modification of meteorological processes. Previously, these methods were widely used in seven wine-growing regions until 1987 (Mahmudov, 2014). Today, such methods should be applied nationwide to ensure food security and protect agricultural production.

Due to war-related disruptions over the past 23 years, protection of agricultural fields against hail has been largely neglected. From 1974–1984, anti-hail measures yielded an efficiency of 13,000 rubles, whereas from 1987 onward, farm losses have significantly increased. Modern systems worldwide now employ automated radar-based technologies, computing equipment, and missile complexes (e.g., “Neba” and “Kristal”) to prevent hail, including artificial rainfall and active influence techniques in hail formation zones. Applying these methods in Azerbaijan could increase protection efficiency by 7–8 times, saving an additional 10,000 hectares of crops.

Zoning Azerbaijan based on hail impact on populations and economic activities relies on synoptic-climatology research (Madatzadeh, 1957). This study divided the Republic into six regions according to hail exposure, analyzing recurrence from sea level to high altitudes. We have refined this zoning to account for economic damage to agriculture and settlements. The primary indicator was hail-induced damage to total agricultural productivity and settlements in administrative districts. Based on the 2020–2025 data, Azerbaijan can be zoned as follows:

- I. High-risk zones: Territories above 1,500 m altitude across Gazakh-Tovuz, Ganja-Dashkasan, Shaki-Zagatala, Nakhchivan AR, East Zangezur, and Karabakh regions, covering over 1,500 settlements (State Statistics Committee of the Republic of Azerbaijan [AzSTAT], 2022). Hail occurs 4–8 times per year, with diameters of 10–15 mm and occasionally >20 mm, causing severe damage to viticulture, horticulture, potato cultivation, and agricultural infrastructure.
- II. Medium-risk zones: Foothills and regions at 1,000–1,500 m altitude, including 450 settlements in Karabakh (Tartar, Agdam, Khojavend), Guba-Khachmaz, Mountainous Shirvan, and Nakhchivan AR (AzSTAT, 2022). Hail occurs 2–4 times per year, with diameters of 5–10 mm,



occasionally 10–15 mm, causing localized agricultural and building damage (State Statistics Committee of the Republic of Azerbaijan [ARSK], 2010).

- III. Low-risk zones: Lankaran–Astara, 46 settlements at 500–1,000 m in Nakhchivan AR (mainly Araz-bay plains) and Mountainous Shirvan (Gobustan region) (AzSTAT, 2022). Hail occurs 0–2 times per year, causing very limited damage to vegetation.
- IV. Hail-free zones: Semi-desert areas below 200 m, partly up to 500 m, including Baku, Absheron-Khizi, Central Aran, Mil-Mugan, Shirvan-Salyan, coastal Guba-Khachmaz, Araz-side parts of Jabrayil and Zangilan, and parts of Nakhchivan AR (AzSTAT, 2022).

CONCLUSIONS

In high-risk areas, the implementation of safety nets, early warning systems, and insurance mechanisms is a priority. In medium-risk zones, operational coverage and localized insurance are sufficient, whereas in low-risk zones, monitoring and minimal protection are economically feasible.

The analysis indicates that the extent of hail damage depends on multiple factors, including hailstone size, intensity, wind speed, areal coverage, and the structure of cultivated areas. Hailstones with diameters up to 10 mm cause significant damage to agricultural crops and orchards, while hailstones measuring 10–20 mm and 20–40 mm can completely destroy cultivated areas. They can also damage roofs and windows, and kill poultry and small animals. Consequently, special attention must be given to protecting agriculture and infrastructure from hail in the study area.

Based on personal observations, hydrological and meteorological research, and analysis of existing statistical and scientific literature, the following conclusions regarding the socio-economic and geographical impact of hail in the Republic of Azerbaijan were drawn:

1. Across most regions of the republic, the average annual number of hail days in 2020–2025 decreased significantly compared to the pre-1990 period. Despite this reduction, agricultural damage has increased substantially due to insufficient control measures and poorly organized insurance compensation.
2. Hailstorms in the Lesser Caucasus regions, Gazakh-Tovuz, Ganja-Dashkasan, East Zangezur, Karabakh, and Nakhchivan Autonomous Republic have caused severe economic losses, particularly in mountainous areas. In the Greater Caucasus, the Shaki-Zagatala and Guba-Khachmaz regions, as well as the plains and foothills, and the lower and middle mountainous zones of Mountainous Shirvan economic region, have been most affected.
3. The effectiveness of hail control efforts prior to the 1990s averaged 9 million rubles. Costs incurred for organizing and implementing protective measures were recovered on average 7–8 times, demonstrating strong economic justification.
4. The application of active anti-hail technologies and concepts used internationally, combined with an analysis of past anti-hail operations in Azerbaijan, provides conditions for effectively preventing hail-related problems in the future. Restoring comprehensive anti-hail measures can substantially reduce expected damage and support economic development in hail-prone regions.

In recent years, Azerbaijan has primarily relied on rudimentary methods to combat hail. In areas where hail is widespread and intense, active and consistent state-level measures are necessary (Ayyubov & Rahimov, 2000). The Cabinet of Ministers should allocate dedicated annual funds for timely prevention of natural processes, and hail mitigation should be considered in regional budget planning.

The creation of a comprehensive network for combating hail is a key research priority. International studies highlight the importance of understanding hail formation physics and developing methods for active intervention (Ismailov, 2014). Decades of theoretical and experimental research in cloud physics have enabled the development of effective methods to artificially influence meteorological processes. Historically, these methods were applied widely in seven wine-growing regions until 1987 (Mahmudov, 2014). Currently, these measures should be implemented nationwide to ensure food security and promote local agricultural production. Applying these systems, along with newly developed forecasting methods, can increase the efficiency of protective measures by 7–8 times and save an additional 10,000 hectares of crops. Expanding and applying these techniques will require significant capital investment across the republic. Unlike other natural disasters, the most universal method for combating hail involves inducing artificial rain by introducing crystalline reagents into hail-forming clouds, neutralizing their destructive potential. In Azerbaijan, it is recommended to employ two of the four independent methods for influencing hail-producing clouds—rocket and artillery—over aviation and ground-generator approaches for optimal efficiency.

Declarations

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Competing interests

The author(s) declare that they have no financial or non-financial competing interests relevant to the content of this article.

Author contributions

Conceptualization: N.P; K.M; Methodology: N.P; Data curation: Z.A; Formal analysis: N.P; Investigation: Z.A; Visualization: K.M; Writing – original draft: N.P; Writing – review & editing: K.M. All authors have read and approved the final version of the manuscript.

Data availability

All data supporting the findings of this study are included in the article and its supplementary materials.

Ethical approval

Not applicable: this study did not involve human participants, animal experiments, or sensitive personal data requiring ethical approval..

Informed consent

Informed consent to participate was obtained from all participants.

Use of AI tools

The author(s) used Google Gemini 3.1 solely for language and style editing. All suggested changes were reviewed individually. Responsibility for the published content remains with the author(s).

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