MAY 2024 FLOODS IN ARMENIA:

Documenting and Understanding Disaster in Lori and Tavush regions, 24–26 May 2024

EVENT ANALYSIS

YEREVAN 2025

MIA Educational Complex
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ARMENIA - АРМЕНИЯ

HYDROMETEOROLOGY AND MONITORING CENTER

EDUCATIONAL COMPLEX OF THE MINISTRY OF INTERNAL AFFAIRS

OF THE REPUBLIC OF ARMENIA SNCO

HYDROMETEOROLOGY AND MONITORING CENTER SNCO
OF THE MINISTRY OF ENVIRONMENT OF THE REPUBLIC OF ARMENIA

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Table of Contents

Abbreviations

AAR	After-Action Review
ADB	Asian Development Bank
Armhydromet	Hydrometeorology and Monitoring Centre
CMSA	Crisis Management State Academy
DG ECHO	Directorate General for European Civil Protection and Humanitarian Aid Operations
Disasters Charter	International Charter: Space and Major Disasters
DRR	Disaster Risk Reduction
DRRNP	Disaster Risk Reduction National Platform
EMS	Emergency Management Service
EO	Earth Observation
ERCC	Emergency Response Coordination Centre
EUCPT	European Union Civil Protection Team
EWS	Early Warning System
FAO	Food and Agriculture Organisation
FOEN	Swiss Federal Office for the Environment
GIS	Geographic Information System
IASC	Inter-Agency Standing Committee
IOM	International Organisation for Migration
ISTC	International Science and Technology Centre
MHPSS	Mental Health and Psychosocial Support
MIA	Ministry of Internal Affairs of the Republic of Armenia
MIRA	Multi-Sector Initial Rapid Assessment
MoE	Ministry of Environment of the Republic of Armenia

MTAI	Ministry of Territorial Administration and Infrastructure of the Republic of Armenia
NGO	Non-Governmental Organisation
NWP	Numerical Weather Prediction
PDNA	Post-Disaster Needs Assessment
SDC	Swiss Agency for Development and Cooperation
SDG	Sustainable Development Goals
SERTIT	Service Régional de Traitement d'Image et de Télédétection
SHA	Swiss Humanitarian Aid Unit
UAV	Unmanned Aerial Vehicle
UCPM	Union Civil Protection Mechanism
UNDP	United Nations Development Programme
UNDRR	United Nations Office for Disaster Risk Reduction
UNFPA	United Nations Population Fund
UNHCR	United Nations High Commissioner for Refugees
UNICEF	United Nations Children's Fund
UNOSAT	United Nations Satellite Centre
WBG	World Bank Group
WFP	World Food Programme
WHO	World Health Organisation

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Executive summary

The northern regions of Armenia experienced heavy rains in May 2024, which led to severe floods and caused great damage and disruption to communities, especially in the Lori and Tavush regions. The government of the Republic of Armenia reacted immediately, providing the affected communities with emergency support and requesting international assistance with damage analysis (roads, bridges, riverbank protection) and the identification of the disaster's main causes, among other things. Switzerland responded at once and deployed a rapid response team from the Swiss Humanitarian Aid Unit (SHA) composed of structural and hydraulic engineers, architects, and experts in disaster risk reduction (DRR). A technical assessment report was handed over to the Armenian government with key findings and recommendations for immediate, short- and medium-term actions.

Armenia is repeatedly confronted with floods and mudflows. Documenting and drawing lessons from the severe floods in May 2024 is important for building back better and reducing disaster risks in future. The Educational Complex of the Ministry of Internal Affairs of the Republic of Armenia (MIA) and the Hydrometeorology and Monitoring Center (Armhydromet) of the Ministry of Environment of the Republic of Armenia (MoE) therefore decided to jointly conduct an event analysis with the expert support of the Swiss Agency for Development and Cooperation (SDC) and the Swiss Federal Office for the Environment (FOEN).

The study is based on an integrated risk management concept, considering all natural hazards and responsible parties (public and private) in the planning and implementation of measures to reduce and manage risks. The study includes data collected from meteorological and hydrological stations, on-site field observations supported by spatial data analysis, and hydraulic modelling based on UAV-based aerial survey (drone) images.

The main **findings** of the study are:

1. **The flood event of 26 May 2024 was the result of prolonged precipitation, affecting the whole basin of the Debed and Aghstev rivers.** Although the precipitation recorded at individual stations was not unusual, the precipitation recorded across the entire area constituted a highly unusual event.
2. **Snowmelt was not among the causes of the flooding.** The available meteorological stations did not observe any snow cover over the Debed and Aghstev river basins.
3. **The event was larger in the River Debed than in the River Aghstev.** In the Aghstev river basin, buildings that were constructed too close to the water were damaged, parts of streets were eroded, and buildings constructed in the backwater area of a dam were damaged. In the Debed river basin all major tributaries eventually experienced floods. High discharges were accompanied by significant sediment transport, which likely contributed to high infrastructure damage.
4. **Much of the damage was caused by the following defects:**
    a. **Inadequate maintenance of protection walls**, which made it easy for the river to enter pre-existing holes or erode deteriorated material, causing the wall to collapse.

   b. **Unfavourable alignment of the river's water flow due to old structures** that diverted the water to the side wall, causing it to erode.

   c. **Generally weak foundations of protective structures**, which allowed undercutting. Insufficient foundation strength of the bridge pillars, which were undermined, causing the bridge to become unstable and in some cases collapse.

   d. **Construction in flood-prone areas.** Such practices should be generally prohibited. Otherwise, the structures would need to receive special protection (object protection).

5. **The order of magnitude of the measured discharge can be confirmed.** Hydraulic modelling was used to reproduce the water levels during the 2024 floods for specific sections.
6. **However, the modelling shows that the observed damage and water levels can also be reproduced with discharge volumes that are lower than the measured values** – due to backwater effects, sediment transport, etc.
7. **Important modelling findings were only possible thanks to the field inspection** (recording of cross sections, understanding of flow paths and process dynamics during the event, etc.).
8. **The floods in Lori and Tavush highlighted several governance shortcomings** that hindered effective disaster preparedness, response, and recovery. These failures can be categorised into issues relating to early warning systems, coordination, infrastructure resilience, and post-disaster support.

To conclude, the floods of May 2024 in the Lori and Tavush regions served as a warning to verify Armenia's level of preparedness for natural, unusual and unexpected events, which may occur more frequently due to climate change and other emerging challenges. The key finding of the study is therefore that lessons must be learned from the disaster at the highest-possible level. The best-available technological and specialist capacities should be leveraged and the resulting knowledge transferred to ensure better preparation and organisation in disaster risk management.

Even though the floods of May 2024 were caused by heavy precipitation, their devastating impact was caused by a variety of factors, ranging from deficiencies in the construction and maintenance of river infrastructure and the riverbed, to the lack of accurate early-warning data and spatial conflicts between humans and nature.

1. Introduction

On 26 May 2024, severe floods impacted the northern regions of Armenia, claiming lives and causing substantial disruption to communities, critical infrastructure, and economic activities in the Debed and Aghstev river basins in the Lori and Tavush regions. This event underscored the urgent necessity of thorough analyses of the disaster to effectively mitigate future impacts. Understanding risk begins with the meticulous documentation and analysis of each occurrence, providing a robust evidential basis for informed decision-making.

This overview compiles and analyses comprehensive hydraulic data and observational records captured during and immediately after the flood event of May 2024. Initial damage assessments, swiftly documented in the aftermath, provided critical insights into vulnerabilities exposed by the flood. Complementary fieldwork conducted six months later facilitated a reconstruction of the event, identifying shortcomings in disaster prevention, preparedness and response measures.

The findings highlight specific errors and gaps that, if adequately addressed, would significantly reduce future damage and economic losses. Particular attention is given to issues with early warning systems, infrastructure resilience, and community awareness. Recommendations are presented for improvements in these areas, advocating for stronger integration of scientific insights into policy frameworks and community education initiatives. Grounding risk management strategies in solid empirical data and evidence-driven analyses may help reduce disaster risks, enhance preparedness and ensure effective, timely responses to similar natural disasters.

The proposed flood event analysis aims to document these events for the future and to draw lessons that can help improve DRR functions through hydrometeorological monitoring, early warning systems, preparedness for future disaster events, and prevention/mitigation measures.

This publication is an effort to show how various multidisciplinary approaches to analysing the disaster's aftermath can be combined, starting from the definition and observations of phenomena to the precise documentation of their impact. It aims to strengthen the future baseline for disaster-related education enhancement in Armenia and establish complex and precise analytical databases and innovative toolkits.

Practitioners and scientists from the Educational Complex of the MIA, Armhydromet and the experts from the SHA and the FOEN have joined forces to better understand and analyse the floods of May 2024 from a scientific point of view and derive practical lessons from it.

Multi Sector Initial Rapid Assessment (MIRA) (UNDP, 2024b) and Post-Disaster Needs Assessment (PDNA) reports (UNDP, 2024a) were requested and realised by the Government of the Republic of Armenia together with the UN Country Team, the experts from the European Civil Protection and Humanitarian Aid Operations (ECHO), and other local and international partners. However, the analysis of the disaster itself required further exploration.

Figure 1. *Map of Armenia, with hydrological observation points. Source: environmental monitoring: surface water observations of RA, https://meteomonitoring.Am/page/58.*

2. General information

Armenia has a rich cultural and historical heritage and a wide variety of flora and fauna. The country is particularly prone to a range of natural hazards: its location, mountainous topography and climate contribute to the occurrence of floods, droughts, landslides, forest fires, earthquakes and other hazards.

Population density: The population of Armenia is about 3,081,100, of which some 1,973,800 (64.1%) live in urban centres, including 1,142,000 (57.9%) in Yerevan. The north, especially Tavush and Lori, is much more sparsely populated, and some villages are in isolated mountainous areas. This population distribution is a challenge for disaster preparedness and response, due to the inaccessibility of such areas. The population is about 229,400 in Lori and 117,600 in Tavush (Statistical Committee of the Republic of Armenia, 2025).

Natural conditions: The Armenian landscape is marked by its complex and rugged terrain, particularly in the regions of Lori and Tavush. Mountain rivers like the Debed, Aghstev, and Dzoraget have carved deep gorges over the millennia, contributing to the region's vulnerability to natural hazards such as landslides and flash floods.

Lori has a dramatic elevation gradient, with altitudes ranging from 380 metres at the lowest point, in the lower stream of River Debed, to over 3,000 metres in the surrounding mountains, including Mount Achqasar (3,196m) and Mount Lalvar (2,543m).

Tavush, slightly lower in elevation, ranges from about 400 metres in the lowlands to approximately 2,900 metres in the higher mountainous areas, with the peak of Mount Miapor reaching 2,993 metres. The region is heavily forested, with rolling hills, densely wooded valleys, and steep mountain slopes along the Tavush and Aghstev rivers.

The Climate Risk Country Profile for Armenia, prepared by the World Bank Group (WBG) and the Asian Development Bank (ADB), foresees that climate change will lead to more frequent and severe weather extremes in Armenia. Temperature increases are projected to exceed global average warming: the most extreme scenario would see warming of up to 4.7°C by the 2090s compared to the 1986–2005 average, while the best-case scenario would see temperature increases of between 0.9 and 2.5°C. This is a serious threat to human health, livelihoods and ecosystems. Precipitation is expected to reduce by 10 % of the annual norm, and the threat of wildfires is expected to grow. The increased risk of drought in future will pose significant challenges to the livelihoods of rural communities that are heavily dependent on agriculture. A warmer and drier climate is expected to cause dramatic alterations to ecosystems, such as the expansion of drylands and semideserts, loss of forest and species range shifts. There will be great demand for water management infrastructure. The fluctuation in drought and flood periods and the change in rain patterns will also increase the mudflow risks, and this requires more attention to be paid to disaster risk reduction and prevention. Without adaptation and successful disaster risk reduction, these changes are likely to affect food production, deepen income and wealth inequalities and complicate efforts to reduce poverty rates in Armenia (World Bank Group & Asian Development Bank, 2021).

Historical and cultural sites: Armenian cultural heritage, especially in these two provinces, is rich with historical architecture and archaeological monuments. Protecting these cultural treasures from disasters is important, as they are significant touristic locations of national significance.

2.1 Risks and vulnerabilities

The primary disaster risks in Armenia, and particularly in the Tavush and Lori regions, include floods/flash floods, landslides, rockfalls, hailstorms, forest fires and earthquakes. These regions, characterised by their diverse topography, face several natural risks directly related to their elevation, climate, and geological conditions.

In the mountainous areas, especially in Lori, where steep slopes and loose geological formations can be weakened by heavy rainfall or seismic activity, landslides can occur, endangering communities and infrastructure. Additionally, the high levels of precipitation increase the risk of flooding in river valleys, with the potential for floods in lower-lying areas due to the rapid runoff from the mountains.

Earthquakes also pose a significant risk, as both regions are situated in a seismically active area of the Lesser Caucasus, where tectonic movements can lead to severe earthquakes, causing widespread damage due to the vulnerability of some buildings and infrastructure.

The risk of forest fires is high during the dry and hot season (July–September). Moreover, the complex terrain and the presence of deep gorges increase the likelihood of rockfalls, which can be sudden and devastating, particularly in narrow valleys.

In winter, higher-altitude areas in both regions are prone to heavy snowfall, which not only leads to snow accumulation and potential avalanches but also impacts transit routes and accessibility to remote communities. During the snowmelt period this can become an exacerbating factor for flooding as well.

These natural risks necessitate comprehensive disaster management strategies to mitigate their impact on human life and the environment. In line with national legislation, most of the communities have their own plans for disaster risk management, developed together with the rescue service planning specialists. However, these plans often remain unrealised, are often underfunded and lack the necessary resources for effective implementation. Community-based disaster risk reduction initiatives have been developed in some areas, but these are not yet widespread. The overall vulnerability of these regions is compounded by their socioeconomic challenges, including poverty and limited access to services, which hinder the ability of communities to prepare for and recover from disasters.

The floods that occurred in May 2024 in the Lori and Tavush regions marked a turning point in the history of disaster management in Armenia. Despite the documented floods and mudflows in the 20th century, including devastating events in Yerevan (1946) and Goris (1977), a misconception persists in society that floods are not characteristic of Armenia's natural conditions. This perception is fuelled by fragmented historical documentation and a lack of public awareness.

Historical data show that destructive floods and mudflows have occurred at different times and in various regions of the country. Below is a chronology of the most significant events:

Table 1. Historical Overview of floods

Date	Location	Type of Disaster	Consequences / Casualties
25 May 1946	Yerevan	Flood/ mudflow	250 fatalities, extensive destruction
19 May 1959	Lori-Tavush	Flood	Significant damage
14–15 August 1970	Alaverdi, Sanahin, Haghpat	Flood/ mudflows	8 fatalities, significant damage
31 May 1994	Artik	Flood	4 fatalities, dam failure, population evacuation
25 May / 22 June 1997	Goris region	Mudflows	4 fatalities, year-long recovery efforts
24 June 2016	Artik, Shirak Province	Mudflow/ heavy rain	100 people evacuated, infrastructure damaged
25–26 May 2024	Lori-Tavush	Flood	4 fatalities, damage along the Debed river basin

In particular, on the evening of 25 May 1946, a major flood occurred in Yerevan due to the overflow of the Getar, a small river which flows through the city, resulting in the loss of 250 lives and causing extensive damage to the city. The event, referred to in some sources as a mudflow, was triggered by 40mm of torrential rain falling within an hour. It gained significant destructive power due to the rupture of the Jrvezh mound. The powerful flow transported stones up to 3 metres in diameter. At the section entering Yerevan, the peak discharge of the mudflow reached 205m^3/s. The total volume of debris transported was approximately 415,000m^3.

Information on the flooding on 19 May 1959 is scarce, but it is still remembered and mentioned by older citizens in Karkop, Lori as a very severe one.

On the night of 14–15 August 1970, heavy rainfall and the overflow of the Debed and Lalvar rivers, combined with mudflows from the mountain slopes, led to a destructive flood in the city of Alaverdi. Eight people died, and significant destruction was recorded at the Sanahin station and in the Haghpat Monastery.

On 31 May 1994, during a flood in the Karkachun river basin, a dam failure occurred at the Artik Reservoir, resulting in the failure of its regulatory functions. Although the population was evacuated, four people unfortunately lost their lives.

In Goris, disastrous mudflows occurred twice, on 25 May and 22 June 1997, causing severe destruction and the death of four people. Recovery efforts took nearly a year.

On 24 June 2016, the streets in the centre of Artik, Shirak Province, were flooded due to clogged mudflow channels. According to the Ministry of Emergency Situations of the Republic of Armenia, the River Karangu overflowed its banks. Large stones accumulated in the riverbeds of Movrov and Bmbulents. Around 100 people were evacuated.

It should also be mentioned that there is controversy regarding the overview provided by different sources on the major floods. There are inconsistencies in dates (many more dates could be cited here with no clear documentation) and definitions (whether there was flooding or a mudflow), underlining the need for systematisation and research at least of the sources that can be studied.

2.2 Floods and mudflows during the period of May to July 2024: overview of damage

From 24 to 26 May 2024, heavy precipitation in the northern regions of Armenia resulted in devastating floods on 26 May 2024 in the Lori and Tavush regions. The rivers Debed, Aghstev, Dzoraget and Tashir overflowed, leading to significant destruction and loss of life:

- **Human losses and evacuation:** Four people died, and over 2,300 individuals were evacuated from the affected areas. Many families were temporarily relocated to shelters.
- **Infrastructure damage:** The floods inflicted severe damage on transportation and public utility infrastructure. Bridges with regional and community significance were destroyed or damaged, including critical crossings in Ayrum and Karkop. Sections of roads, railways, power lines, gas pipelines, and water supply systems were damaged. Residential houses, schools, and other public buildings were inundated in several settlements.
- **Economic losses:** According to the PDNA carried out with the support of the UN and EU, the damage affected nine consolidated communities in the Lori and Tavush provinces, including Alaverdi, Dilijan, Gyulagarak, Ijevan, Noyemberyan, Pambak, Stepanavan, Tashir, and Tumanyan. The assessment covered both direct destruction and indirect losses in agriculture, business, and other sectors.

  The total estimated damage was over USD 49 million (UNDP, 2024a, pp. 14-18).

In total, 13 cases of floods and river overflows were recorded in 2024, resulting in 4 deaths (3 in Lori and 1 in Tavush, on 26 May), and 496 people were rescued and evacuated (403 in Lori, 93 in Tavush). Twelve of these events were caused by river overflows, and one by a hydraulic infrastructure failure.

Some of the severe **floods** mentioned occurred in May (8 cases), June (2), and July (3) as follows:

- **Yerevan (4 May 2024)** – Streets and residential buildings flooded due to the collapse of a retaining wall along a channel.
- **Armavir Province (12 May 2024)** – Pastures and arable land flooded.
- **Lori Province (17 May 2024)** – Overflow of the River Debed caused flooding of residential and farm buildings.
- **Lori Province, Karkop (11 June 2024)** – Pedestrian bridge collapsed again, and water supply was disrupted.
- **Gegharkunik (13 and 27 June 2024)** – Due to the overflow of the River Getik, houses and livestock sheds were flooded, animals were evacuated.
- **Lori Province (2 July 2024)** – Bridge in the village of Hobartsi was destroyed again.
- **Tavush (28 July 2024)** – 55 people were trapped in the ‹Skazka’ recreational area, 51 evacuated (including 46 children).

Mudflows also occurred in 2024:

- **1 June 2024, village of Medovka, Lori** – Mudflows flooded basements and sheds; 200 head of livestock evacuated.
- **10 June 2024, Alaverdi–Vanadzor highway** – Mudflows blocked the road and flooded railway tracks.

- **11 June 2024, Vayots Dzor** – Mudflows made the road to Gndevank Monastery impassable.
- **28 July 2024, village of Gokhtanik** – A mud- and rock-flow covered a livestock yard, killing 65 small ruminants.

These disasters were mostly associated with torrential rain, although other causes such as snowmelt or hydraulic structure failure are possible, though significantly rarer. For a comprehensive understanding, these phenomena would need to be reviewed and analysed together.

In 2024, 40 cases of torrential rain were recorded (for comparison: 19 in 2023 and 3 in 2022)[1]. **Distribution by month:** March – 1 case, May – 19 cases, June – 5 cases, July – 6 cases, August – 2 cases, September – 4 cases, October – 3 cases.

By region: Aragatsotn – 5 cases, Ararat – 3 cases, Armavir – 1 case, Gegharkunik – 2 cases, Lori – 8 cases, Kotayk – 5 cases, Tavush – 3 cases, Yerevan – 13 cases.

As a result of torrential rain, 67 people were evacuated and 82 were relocated to safe areas. Reported consequences include flooded streets, damage to and blockage of vehicles, flooding of residential and public buildings, collapsed walls of warehouses and private homes, damaged fences, and destruction of gas pipelines. Torrential rain also triggered river overflows with devastating consequences.

Rescue units carried out water pumping operations in homes, buildings, and public spaces. The number of torrential rain events registered in 2024 was the highest in the past ten years.

The events documented in 2024 clearly demonstrate that, despite the widespread perception of Armenia as a relatively dry country, floods represent a recurrent and escalating hazard that cannot be ignored. Historical records, along with recent disastrous events in the Lori and Tavush regions, underscore that hydrometeorological hazards are not anomalies, but rather a significant risk exacerbated by climate variability, inadequate infrastructure, and limited risk awareness.

Floods can cause much more damage when early warnings and alarms are not properly issued. Rapid-onset floods – known internationally as flash floods and often linked to intense rainfall and compounded by human-induced vulnerabilities – leave little time for reaction. This reinforces the critical importance of shifting from reactive to anticipatory risk governance.

In line with the priorities of the Sendai Framework (UNDRR, 2015) and global climate change adaptation agendas, building resilience in Armenia must include the development and clear operability of **multi-hazard early warning systems,** that should be accessible to the whole population of the Republic. Moreover, proactive and **anticipatory actions** must be integrated into national and local disaster risk management strategies, supported by accurate data, risk mapping, and public awareness.

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[1] The information is provided by the Crisis Management National Center of the Ministry of Internal Affairs of the Republic of Armenia.

3. Meteorological and climatological analysis

The wettest May observed in Armenia after 1936 was in 2024, according to the precipitation observations from Hydrometeorology and Monitoring Center (Figure 2). Moderate and heavy precipitation observed on 24–26 May produced disastrous floods in the northern part of Armenia, in the Debed and Aghstev river basins. During those days, Armenia was affected by an atmospheric frontal system and cyclonic activity induced by the interaction between the polar airmasses in the northeast and moist tropical airmasses to the southwest of Armenia. This atmospheric circulation caused widespread convection, clouds and precipitation over northern regions of Armenia (Lori and Tavush) as can be seen in the satellite image taken at 16:30 UTC on 25 May (Figure 3).

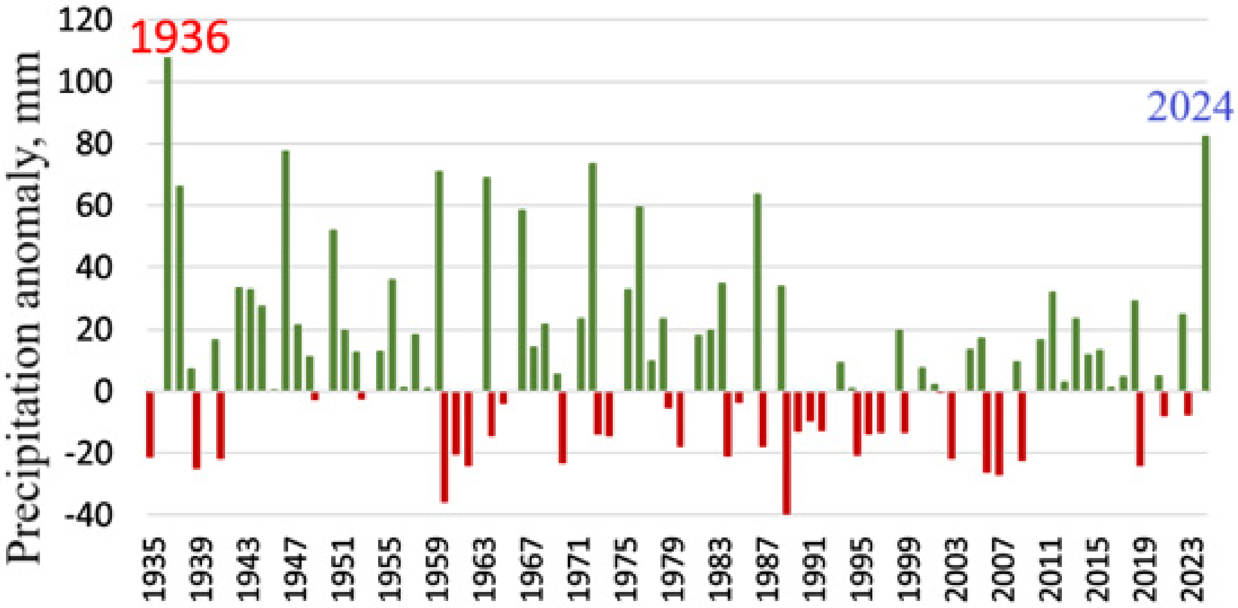

Figure 2. *Monthly precipitation anomalies over Armenia in May in the period 1935–2024*

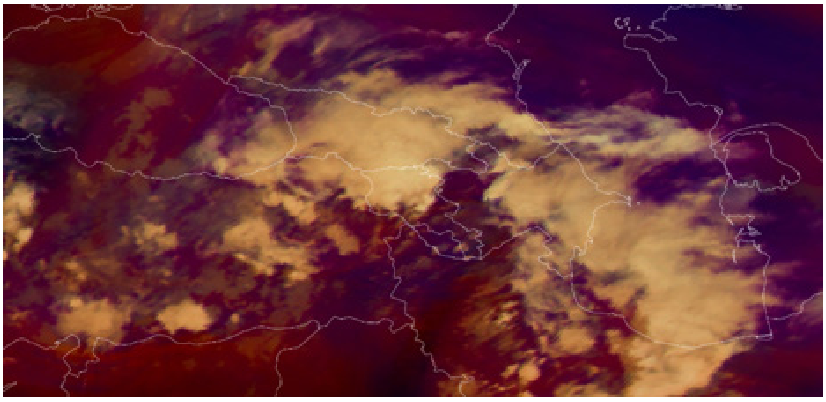

Figure 3. *EUMETSAT's satellite image at 16:30 UTC on 25 May 2024*

Observations show that the 3-day total precipitation amounts (from 24 to 26 May) exceeded 30-40 mm over the entire river basins of Debed and Aghstev, while few meteorological stations observed over 80 mm total precipitation (Figure 4, left panel). Orographic precipitation enhancement likely contributed to the observation of local heavy precipitation. The temporal variations of observed daily rainfall show that the peak intensity of precipitation was observed on 26 May, when most of the meteorological stations located in Debed and Aghstev river basins observed above 30 mm daily rainfall (Figure 4, right panel). More detailed analysis of rainfall intensity derived from hourly measurements of automatic weather stations showing that rainfall intensity started to increase in the evening hours of 25 May, just before and during the formation of nighttime extreme flash floods on 26 May (shown in Figure 5).

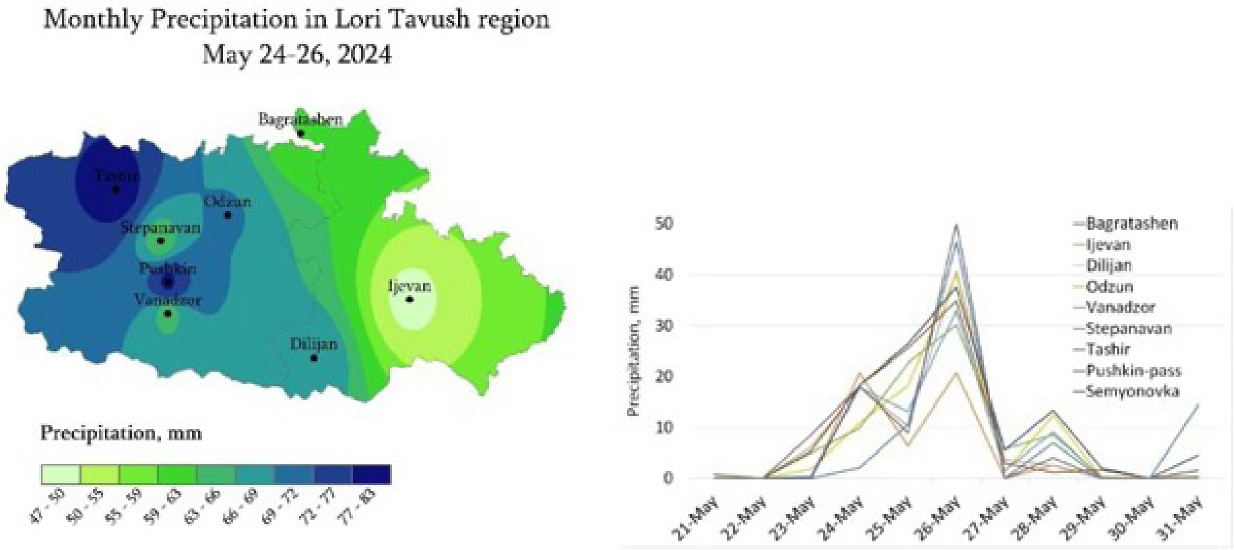

Figure 4. *Total precipitation amount over Lori and Tavush observed from 24 to 26 May, 2024 (left panel) and daily rainfall amount observed at nine meteorological stations over Debed and Aghstev river basins (right panel) based on observations from nine meteorological stations.*

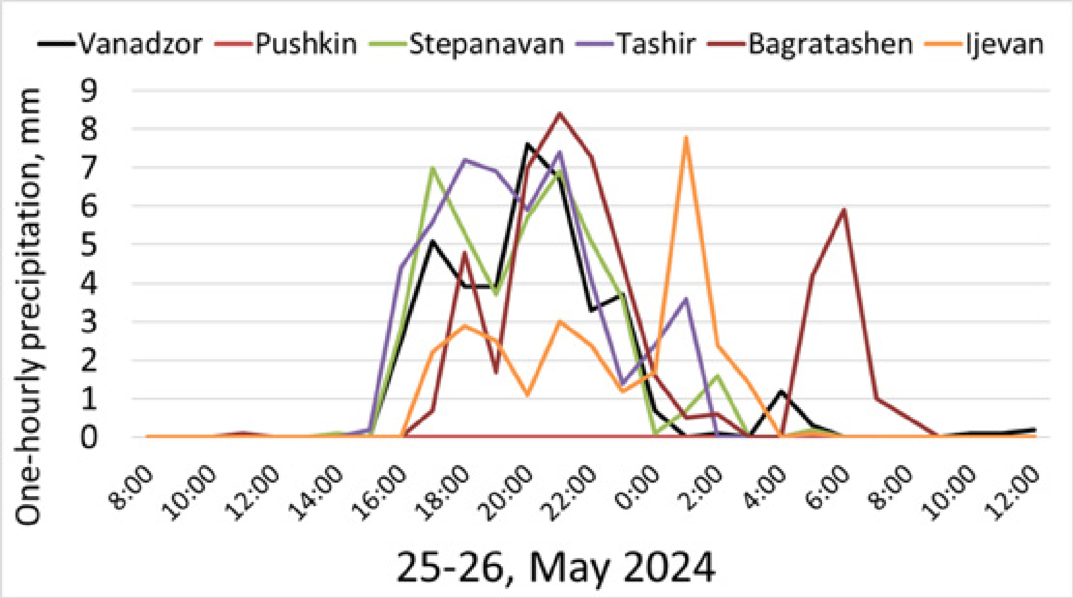

Figure 5. *Hourly precipitation rates on 25-26 May 2024 observed by automatic weather stations located in Debed and Aghstev river basins*

It is worth noting that the high-altitude meteorological stations of Pushkin Pass and Semyonovka located at around 2,100m above sea level did not observe any snow cover during the last ten days of May. It is also worth noting that April was extremely warm and dry, which effectively depleted the snow cover accumulated in the winter season over high-altitude mountain areas of Armenia. This reduces the contribution of rapid snowmelt in the formation of floods on 26 May, though there were no in-situ snow observations at higher altitude areas of the Debed and Aghstev river basins (over 2,500m above sea level). Most of the meteorological stations reported heavy rainfall on 25 May, which was accompanied by thunderstorms. However, Semyonovka station, located at the upper flows of the Aghstev river basin reported graupel on 25 May. This suggests that graupel and hail could be observed over the Debed and Aghstev river basins during those days, though most of the meteorological stations observed heavy rainfall.

A statistical analysis of daily precipitation amounts derived from the observations of the meteorological stations over the Debed river basin over the period 1961–2024 was performed. The results showed that the average three-day total precipitation (from 24 to 26 May) over the entire Debed river basin was a very rare event, with the recurrence interval estimated to be more than 100 years. However, when considering the total precipitation for different time periods at individual stations, the recurrence intervals were much lower. This suggests that the flood event of 26 May 2024 was caused by heavy precipitation affecting the large areas of the Debed and Aghstev river basins, as well as by precipitation events observed in the preceding two days.

Therefore, it is likely that moderate to heavy rainfall observed from 24 to 26 May over the entire Debed and Aghstev river basins produced the nighttime floods on 26 May. The rainfall during the preceding days favoured an increase in soil moisture which likely efficiently converted rainfall to surface flow. However, the lack of soil moisture observations at this stage makes it challenging to better understand this impact. Local orographic precipitation enhancement was likely important in the formation of heavy precipitation and flash floods over the Debed and Aghstev river basins. However, the impact of orographic precipitation enhancement over the Debed and Aghstev river basins could be underrepresented by the existing observational network with most of the stations located below 2,000m above sea level.

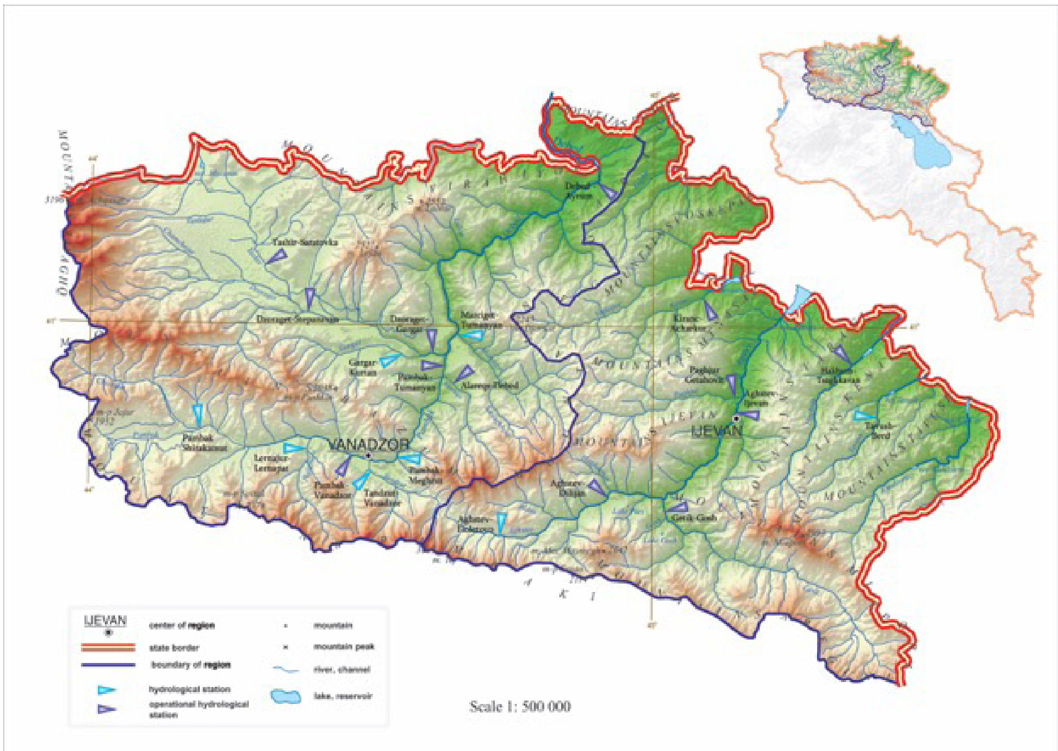

Figure 6. *Lori and tavush regions, with hydrological observation points.*

4. Hydrometrical analysis and observations from the field

4.1 Hydrological regime of the Debed and Aghstev rivers

Description of the Debed and Aghstev rivers

The River Debed is the right tributary of the River Khram and is one of the largest rivers in the Republic of Armenia in terms of length, water volume, and catchment area. The total length of the river, including the Pambak tributary, is 176km, of which 154km is within the borders of Armenia. The catchment area within Armenia is 3,790km^2 (total 4,080km^2). It is a typical mountain river, characterised by spring floods and a prolonged low-water period (Mnatsakanyan, 2007, p.190).

The River Debed is formed by the confluence of two large tributaries: the Pambak and Dzoraget rivers. **The River Pambak is one** of the main tributaries of the Debed, and originates in its upper reaches at an altitude of 2,100m. The River Pambak is 84km long, with a catchment area of 1,370km^2. The largest tributaries of the River Pambak are the Chichkhan and Tandzut rivers.

The River Dzoraget is the main tributary of the River Debed. It originates in the Javakhk mountains at an altitude of 2,320m and is 67km long, with a catchment area of 1,460km^2. The largest tributary of the River Dzoraget is the River Tashir, which is 54km long and has a drainage basin area of 470km^2. The River Tashir flows into the River Dzoraget 28km from its mouth.

Other main tributaries of the River Debed include the Martsiget and Shnogh rivers, which flow into the River Debed 4km and 40km downstream of the mouth of the River Dzoraget, respectively (see Figure 6).

In the Akhtala area, the River Pambak contributes 34% of the River Debed annual flow, the River Dzoraget contributes 48%, and the remaining 18% comes from the Debed side flow.

The River Aghstev originates from the northern slopes of the Pambak Mountains at an altitude of 3,000m. It is one of the right tributaries of the River Kura and is 121km long (81km within Armenia), with a catchment area of 2,500km^2 (1,730 km^2 within Armenia).

The main left-bank tributaries of the River Aghstev are the Bldan, Haghartsin, Paghjur, and Voskepar rivers (the latter being 58km long). The main right-bank tributaries include the Getik, the largest tributary of the River Aghstev (58km long with a catchment area of 596km^2), and the Naltiget.

Hydrological regime of rivers

The Armhydromet hydrological monitoring observation network in the Debed and Aghstev river basins includes 21 hydrological observation points/posts, of which 13 are included in operational hydrological works. Observations at the observation points are carried out twice daily, at 08:00 and 20:00, mainly with mechanical instruments and equipment. Water level observations are carried out mechanically, using hydrometric gauging staffs.

The long-term hydrological observations made it possible to assess the hydrological regime of the rivers. This is presented in the tables in Figure 7 below.

The Debed and Aghstev rivers are primarily fed by melt and rain waters, meaning that surface flow predominates. The highest flow is observed in May, followed by April and June.

Spring floods are one of the main phases of the water regime of the Debed and Aghstev rivers, as well as their tributaries. The formation of spring floods is influenced by meltwater, rain, and groundwater. Spring floods typically begin in the second half of March and continue until June, sometimes lasting until mid-July. During the spring flood period, an average of 60–65% of the annual flow passes through the rivers in the basins (Figure 7).[2]

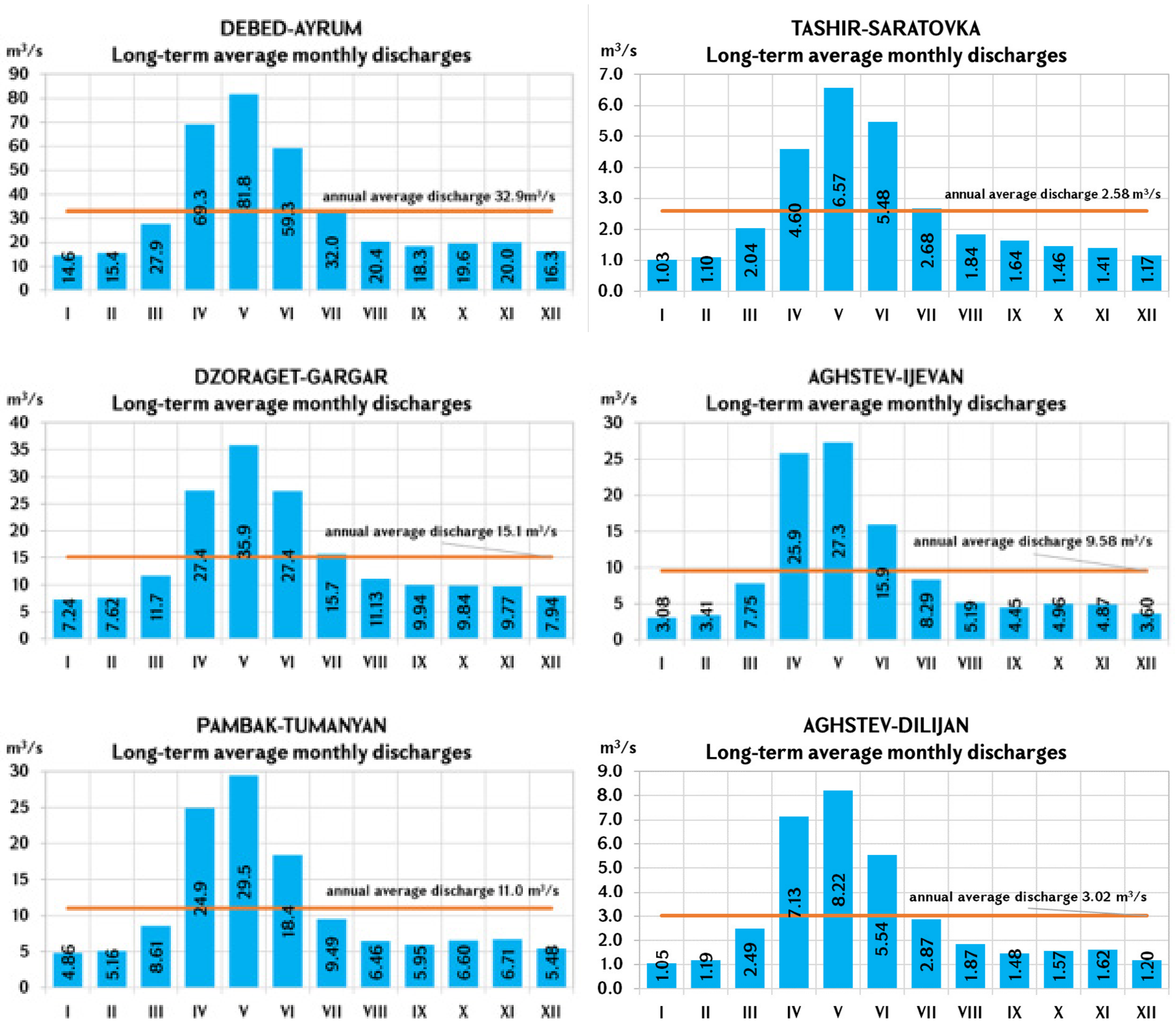

Figure 7. *Long-term average discharges at selected stations*

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[2] Annual data on surface water resources of the Republic of Armenia 1930–2024, Armhydromet hydrological database.

In the Debed and Aghstev river basins, maximum discharges are primarily observed during spring floods, with the exception of certain cases when heavy rains during the summer–autumn period cause discharges that exceed those observed during the spring floods. In some instances, the maximum discharges during spring floods are accompanied by significant flooding of settlements, arable land, various buildings and enterprises, and hydraulic structures.

4.2 The flood event of 26 May 2024

The maximum discharges and the resulting floods in the Debed river basin on 26 May 2024 were unprecedented in both nature and intensity. As a result of these floods, the structures (bridges, ropeways/crossings), tools and equipment intended for hydrometric work at the Armhydromet hydrological observation points in the Debed and Aghstev river basins were completely destroyed. In almost all stations, hydrometric equipment was partly washed away or rendered unusable due to waterlogging (Debed-Ayrum, Dzoraget-Gargar, Dzoraget-Stepanavan, Tashir-Saratovka, Pambak-Shirakamut, Aghstev-Fioletovo, Kiranc-Acharkut).

Floods were observed during the night and morning hours of 26 May 2024, affecting the entire Debed and Aghstev river basins in the Lori and Tavush regions. Due to the continuous heavy rainfall, sharp increases in water levels were observed in the Debed and Aghstev river basins, rising more than two metres above the previous day's levels (Figure 8). As a result, surrounding areas were flooded, causing significant damage to parts of settlements and leading to human losses.

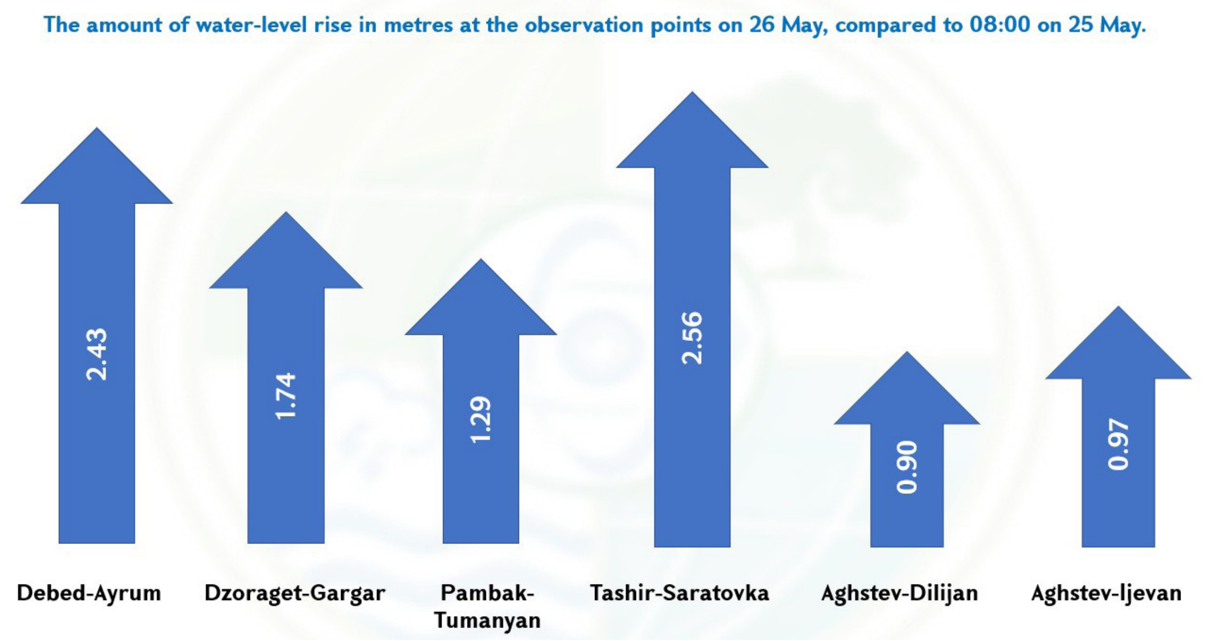
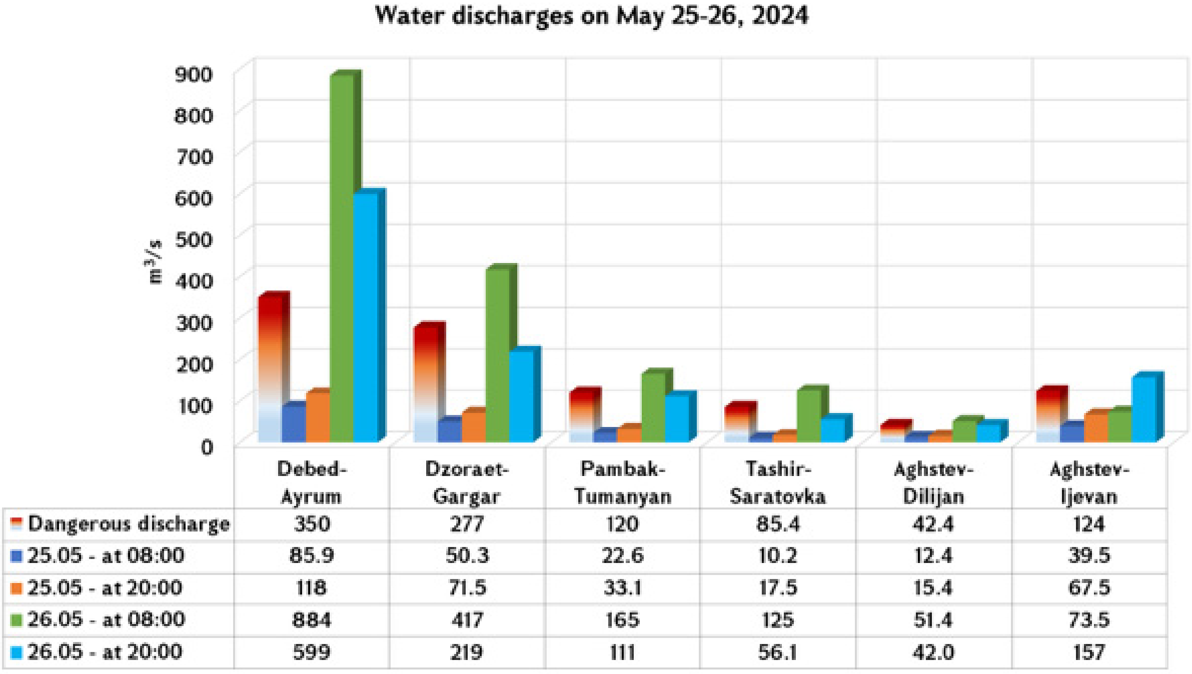


Figure 8. *Rise of water level at different observation points*

According to Armhydromet observation data, the discharge increased by 766m^3/s at the Debed-Ayrum hydrological observation post on 26 May compared to 20:00 on the evening of 25 May, by 346m^3/s at the Dzoraget-Gargar hydrological observation post, and by 108m^3/s at the Tashir-Saratovka observation post (Figure 9).



	Debed-Ayrum	Dzoraet-Gargar	Pambak-Tumanyan	Tashir-Saratovka	Aghstev-Dilijan	Aghstev-Ijevan
🟥 Dangerous discharge	350	277	120	85.4	42.4	124
🟦 25.05 - at 08:00	85.9	50.3	22.6	10.2	12.4	39.5
🟧 25.05 - at 20:00	118	71.5	33.1	17.5	15.4	67.5
🟩 26.05 - at 08:00	884	417	165	125	51.4	73.5
🟦 26.05 - at 20:00	599	219	111	56.1	42.0	157

Figure 9. *Water discharge estimated on May 25-26, 2024*

It should be noted that the water discharge reaches a dangerous level at 350m³/s at the Debed-Ayrum hydrological observation point, 277m³/s at the Dzoraget-Gargar hydropost, and 85.4m³/s at the Tashir-Saratovka observation post.

In order to assess the magnitude of the maximum discharges formed during the floods, on 3–6 June 2024, Armhydromet carried out levelling and field measurement work at hydrological observation points, based on water level traces, to determine the maximum increase in water level and to calculate the maximum discharges that occurred. The results of the field work were developed and analysed, taking into account the available historical data. According to assessments, the maximum water level at the Debed-Ayrum hydrological observation point was 874cm (484.37m above sea level). The maximum instantaneous water discharge at the hydrological post was 884m³/s, which is the absolute maximum during the entire observation period. Such high-water discharges were observed in the River Debed on 19 May 1959: the maximum water discharge at the Debed-Ayrum hydrological observation station was 759m³/s.

The maximum water level at the Dzoraget-Gargar hydrological observation point was 752cm (981.04m above sea level), and the maximum instantaneous water discharge observed on 26 May was 417m³/s, which is also the maximum for the entire observation period.

The maximum water level at the Pambak-Tumanyan hydrological observation point was 232cm, and the maximum instantaneous water discharge recorded was 165m³/s.

At the Tashir-Saratovka hydrological observation point on 26 May 2024, the maximum instantaneous water discharge was 125m³/s.

The maximum water level at the Aghstev-Dilijan hydrological observation point was 303cm, with a maximum water discharge of 51.4m³/s on 26 May.

The maximum water level at the Aghstev-Ijevan hydrological observation point was recorded at 20:00 on 26 May, having increased by 0.97 metres compared to 08:00 on 25 May, with a water discharge of 157m³/s.

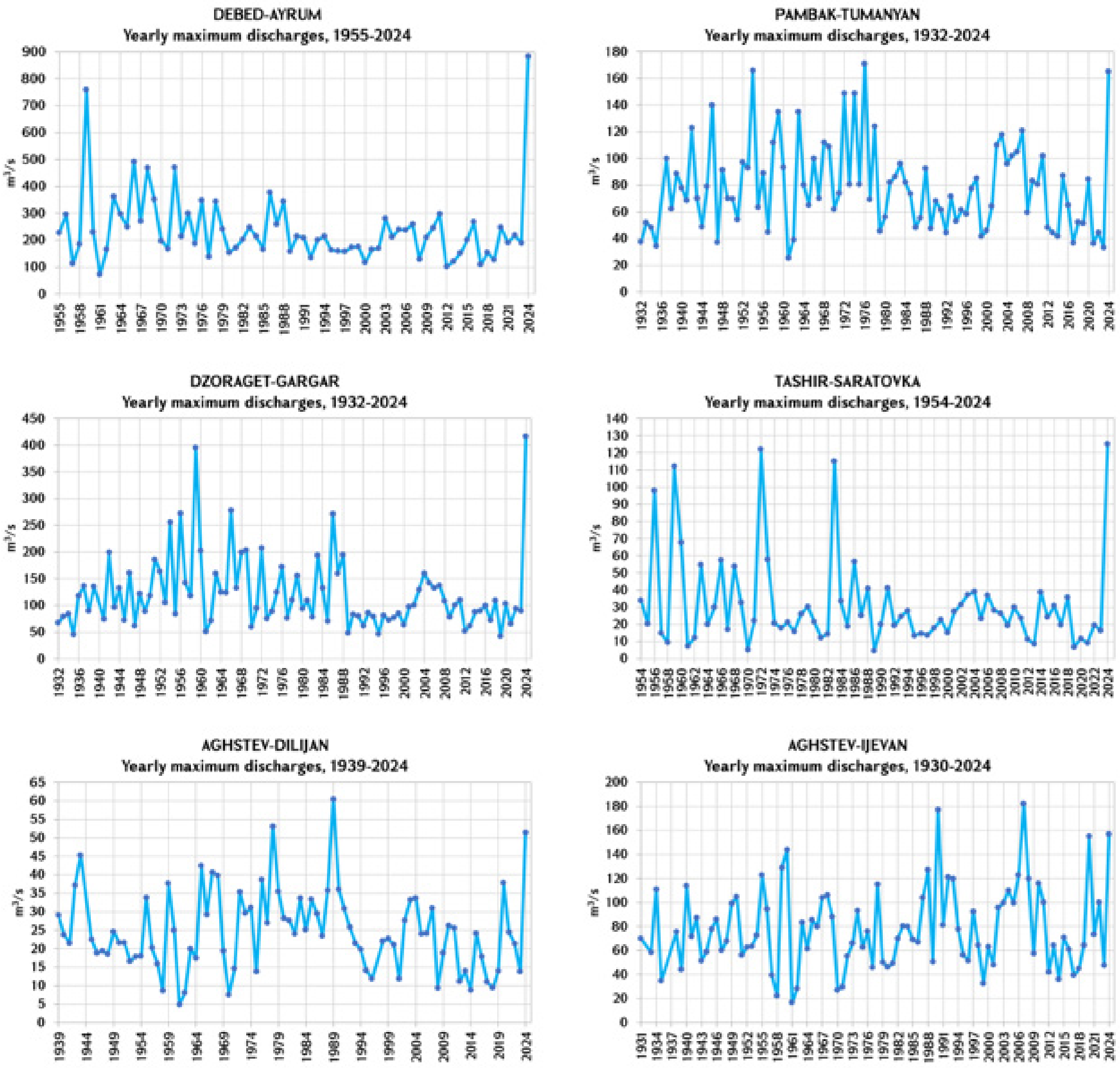


Figure 10. *Yearly maximum discharges*

According to historical observation data, the maximum water discharges observed at the observation points on 26 May were the highest for the entire observation period, and if not the absolute maximum, they were the second or third highest in magnitude.

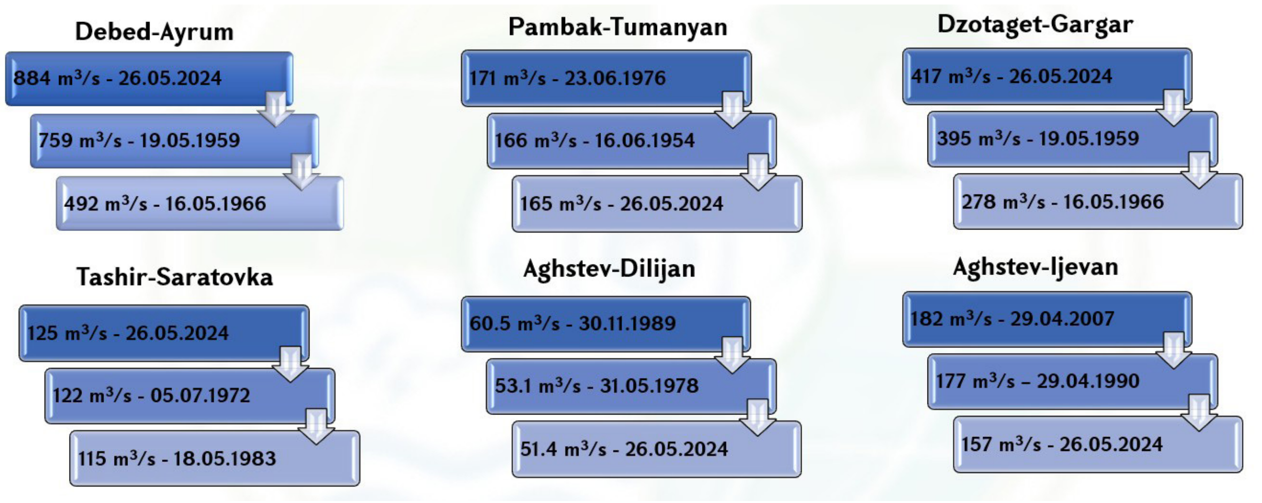


***Figure 11**. Highest discharges at selected stations*

4.3 Observations in the field

As already seen from the precipitation and runoff data, the floods in the Aghstev and Debed river basins were very different. Although the Aghstev experienced high discharges and some damage, this was not comparable to the damage in the Debed river basin, which was an event of far greater magnitude.

The following observations were made in the field.

4.3.1. River Aghstev

Damage was mainly recorded where the river was restricted by human intervention:

- Lateral limitation of the riverbed through construction of infrastructure or buildings: buildings that were constructed too close to the water were damaged in some areas, and parts of streets were eroded. The cross-section at these points was too small, so that in the event of a larger flood, the river can penetrate into the buildings (Image 1).
- Buildings that were constructed in the backwater area of a dam suffered from damage as well. This could have been the result of the particular conditions:
- The Sarnajur (Paghjur) river seemed to be transporting a high bed load during the flood of May 2024. A similar flood occurred at this location in 2007, while another, probably less intense, occurred in 2020. Image 2 illustrates the possible effect of the Sarnajur sediment input with significant deposits in the River Aghstev. The Sarnajur sediment input to the main river may have overloaded the sediment transport capacity of the River Aghstev, resulting in these large sediment deposits downstream of the mouth of the River Sarnajur.
- The dam further downstream led to more sediment accumulations and therefore to a significant bed aggradation. This reduced the cross-section of the river causing the water to enter the buildings (Image 3). Downstream of the dam, the sediment deficit led to increased erosion. This effect might have favoured scour and the undercutting of the Khashtarak bridge several hundred metres downstream of the dam.
- The river has already been cleaned by machinery since the flood.

Image 1. Buildings at the riverside

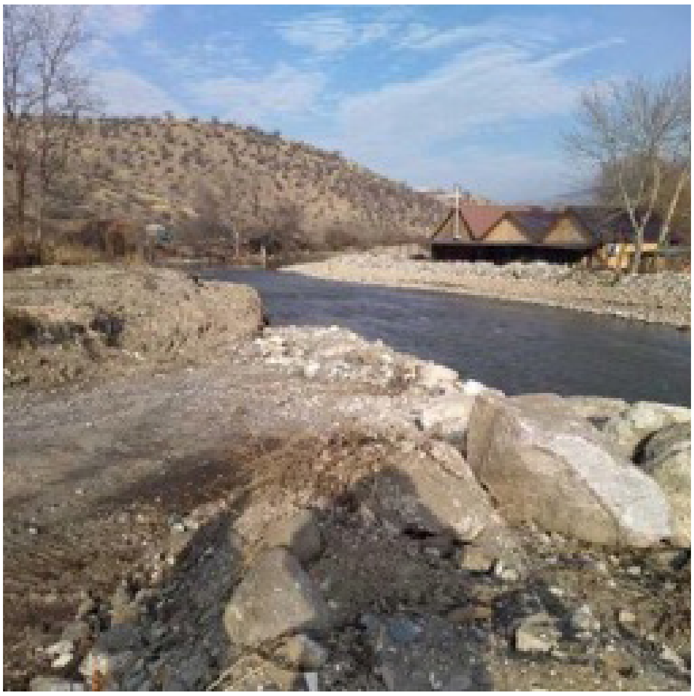


Image 2. River Aghstev in 2022 (left) and in 2024 (right) after the flood

Image 3. Buildings damaged due to bed aggradation

4.3.2. River Debed

As the River Debed flood was an unusual flood of rare magnitude, the damage was also correspondingly high. The main reasons for the damage were:

- **All the major tributary rivers that eventually form the River Debed experienced flooding**

This corresponds to the findings from the precipitation data, indicating that the whole Debed river basin was affected. But interestingly, at the lower stretches of the River Debed, with the exception of the River Marts, only a little activity was found in the tributaries of the River Debed. Further on, no landslides were reported.

- **High discharge with significant sediment transport**

The high discharges led to a high amount of sediment transport in some stretches along the rivers. Sediment deposits on and beside the riverbed alternated with bed and bank erosion. This led to the destruction of various sections of the roads along the river (Image 4).

Image 4. Destroyed road at Karkop

Erosion was mainly observed at bridges, where the piers were undercut causing a failure of the bridge. High sediment transport also caused significant riverbed aggradation in some places.

- **Insufficient cross-sections**

The town of Tashir was greatly affected by the flood. The canal through the town is bounded on both sides by walls around one metre high.

The problem was that the cross-section of the canal was too small to accommodate the entire discharge. The discharge was too high, so the water had to find its way through the village. However, there were also holes in the canal walls through which the water could flow into the houses.

Image 5. Tashir river with accumulations in the river bed

The discharge was largely bed load free. This can be seen in Image 5, where no new bed load accumulations are visible and the grass still is not washed away. However, due to the snow conditions at the time of the visit, it was not possible to see the entire riverbed. But it was evident that the accumulations in the riverbed were old. The riverbed has not been cleaned, so the cross section in the channel has been significantly reduced. It cannot be conclusively determined whether the damage would be smaller if these accumulations had not been there. It nevertheless shows that the regular cleaning of riverbeds is an important issue.

- **Insufficient object protection**

The village of Karkop was greatly affected by the flood (Image 9). The access bridge to the village was completely destroyed and the village itself was flooded. A temporary pedestrian bridge was built and important cables and pipes have been repaired. However, by car, villagers must make a 28km detour to reach the main road on the other side of the river.

The village Karkop was built in around 1937, and has experienced three flood events until now:

- 1959: flood, minor flooding over the walls
- 1985/85: similar event to 1959
- 2024: an order of magnitude larger.

The mention of the 1959 event is particularly noteworthy: upon reviewing Figure 11 (Ayrum), the two highest discharges during the entire measurement series were recorded for 1959 and 2024 at this station.

Up to now, every 30 years – as a rough estimate – the village suffers from a flood from the River Debed.

It must be assumed that some of the damage from the 2024 flood could have been reduced or even prevented if the wall that separates the village from the river had been fully maintained. The wall that separates the village from the river area had several holes through which the water penetrated into the streets and houses (Image 6). In addition, some water also entered from the upstream part of the village (Image 7). A significant part of the water entered the village through the holes shown in Image 7 and Image 8.

In order to prevent further flooding of the village, the wall will need to be repaired. If a bridge to the village were rebuilt at the same location, it should be planned with no piers and be strongly anchored to the terrain at both ends. If a pier were to prove necessary, it should have deep foundations in the riverbed. Modelling (e.g. HEC-RAS) can be used to determine the required level of the bridge so that the channel has sufficient discharge capacity in the event of flooding.

Image 6. Wall with hole were water entered the village of Karkop

Image 7. Hole through which water entered the village of Karkop

Image 8. Another hole in the wall

Image 9. Karkop during the flood

- **Structural issues**

Many structures, such as bridges and protective walls along the river, are old and were built during the Soviet era. Many of these structures were undercut during the 2024 flood, often resulting in the collapse of the structure in question. Above all, many **bridge piers** had inadequate foundations. Examples are:

Image 10. Khashtarak bridge with undercut sidewall

Image 11. Hobardzi bridge

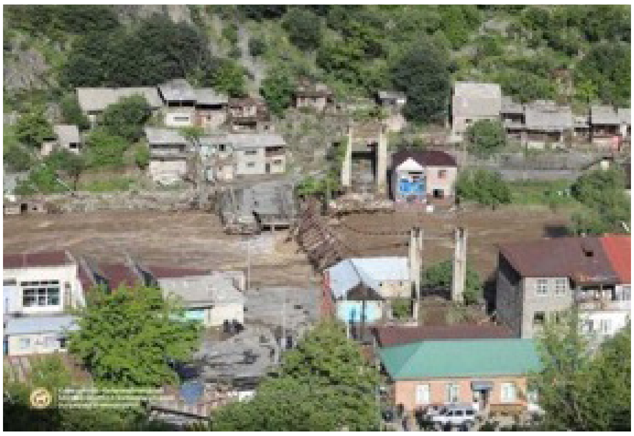


Image 12. Destruction of the bridge at Sanahin

Image 13. Undercut piers of bridge in Alaverdi

Image 14. Akhtala bridge

Image 15. Destroyed bridge in Karkop village

Image 16. Ayrum bridge during the flood

Image 17. Ayrum bridge in December 2024

- **Khashtarak bridge**, Ashtsev river: The mid pier of the bridge was an obstacle for debris and wood (Image 10).
- **Hobardzi bridge**: The dilapidated bridge was destroyed. The pressure of the flood water was difficult to estimate, but it probably played a role in the submerging of the piers (Image 11).
- **Alaverdi double bridge**: An old Soviet bridge and an approximately two-year-old bridge just a few metres downstream cross the River Debed in Alaverdi. The foundations of the old bridge piers were only 50–100cm deep, with two erosive channels cutting through

the piers. The erosion depth at this point was about 1–1.5m. This exposed both bridge piers, leading to destabilisation of the bridge (Image 13).

- **Akhtala bridge**: The bridge almost failed during the event and was later provisionally repaired to permit traffic circulation (Image 14). It was observed that the bridge nearly collapsed due to undercutting and destabilising of the piers.
- **Karkop bridge**: The bridge to the village on the other side of the River Debed was completely destroyed, the foundation was eroded (Image 15).
- **Ayrum bridge**: The collapse of the Ayrum bridge was due to similar causes mentioned above (Image 16 and Image 17).

Many protective walls and riverbank protection structures are in a state of disrepair and would need to be renovated. Furthermore, these structures usually did not have deep enough foundations, were easily undermined by flooding, and ultimately collapsed (Image 18 - Image 21).

Image 18. Undercut lateral protection works

Image 19. Collapsed bank protection works below the confluence of Pambak and Dzoraget rivers

Image 20. Debed river with destroyed bank protection works at Sanahin

Image 21. Destroyed bank protection works at the right side of Debed river at Karkop

Bank and lateral erosion

Bank or lateral erosion occurred where the river was diverted around an obstacle, encountered a construction or hit a bank (Image 22 and Image 23). The eroded bank in Image 24 did not cause any direct damage, but the presence of the dam meant that a large amount of sediment was deposited, making the river downstream highly erosive again.

Image 22. Debed near Akhtala village

Image 23. Debed in Alaverdi

Image 24. Bank erosion downstream of the dam near Sarnajur

Detrimental constructions in the riverbed

Several hundred metres downstream of the Alaverdi bridge are the remains of a dam. Its function was not clear during the field excursion. In the two openings, there might previously have been frame weirs. Nevertheless, the effect of this dam is that the water is diverted directly to the left of the embankment (practically at a right angle, Image 25). It is expected that the embankment will be undercut and therefore fail in the future, as happened some metres downstream during the flood event (Image 26). However, because so much water flowed over the dam, the openings played a minor role. The derived water undercut the wall and it collapsed and was washed away (Image 26). In conclusion, it might be stated that the dam is counterproductive and endangers the bank protection walls on the orographic left side. If there is no other important reason to keep the structure, the removal of the dam is recommended.

Image 25. Remains of a dam diverting water to the protection wall

Image 26. Collapse of the protection wall downstream of the dam

- **Role of the reservoirs**

For many years, it has not been possible to open the frame weirs of the Ijevan reservoir (Image 27 and Image 28), resulting in the continuous aggradation of the reservoir. Debris have accumulated up to three metres below water level.

The effect of the reservoir during the May 2024 flood was not quite clear. Some additional frame weirs obviously existed prior to the flood, damming the water up to the road before breaking. Some remains of the frame weirs are still present, but it could not be determined in detail how exactly the process of destruction started. It was assumed that the damming process in the reservoir did not significantly affect the peak discharge for Ijevan a few kilometres downstream.

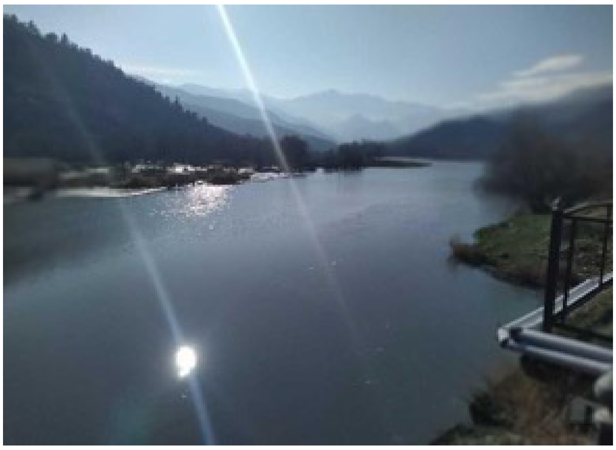


Image 27. Ijevan Reservoir

Image 28. Dam at the Ijevan reservoir

The dam half a kilometre upstream of Khashtarak bridge was constructed only about 10 to 15 years ago according to a short analysis of satellite imagery. The purpose of its construction remains unclear. The effect in May 2024 was an aggradation of the riverbed upstream of the dam due to a reduction of sediment transport capacity, resulting in the damage to the buildings mentioned above.

One hypothesis could be that the Sarnajur sediment input to the main river may have arrived before the peak of the Aghstev flood, reducing the capacity of the main river and resulting in large sediment deposits downstream of the mouth of the Sarnajur. The dammed river led to more sediment accumulations and therefore bed aggradation, causing damage to the buildings.

Downstream of the dam, due to the sediment deficit, the river was further eroded. This effect favoured erosion of the right bank downstream (Image 29) and scour and undercutting of the Khashtarak bridge several hundred metres downstream.

Image 29. Dam upstream of Khashtarak bridge

On the flood plain upstream from the reservoir, much of the bedload has been deposited, but not all of the debris is attributable to the 2024 event.

The role of the reservoir during the May 2024 event is difficult to assess because access to the site was not possible, nor was an informant present.

The peak of the flood was probably on the night of May 26 and the power station may have been unattended.

An attempt has been made to reconstruct the peak. It was assumed that the full volume of water passed through the power station. Bed load transport downstream of the station was marginal.

The river bed below the reservoir seems stable, and contains many coarse boulders. It could be assessed that the bedload input from Dzoraget to the Debed river was not significant.

Image 30. Floodplain upstream of the reservoir

Image 31. Reservoir of Dzoraget river

It is possible that the large floodplain and the reservoir itself stretched the hydrograph of the event (it lowered the flood peak going downstream), but it is not known to what extent. As the flood peak at Kurtan bridge was estimated to be of the same order of magnitude as at the confluence, the peak reduction was not significant.

In conclusion, the role of the reservoir is limited because bed load was held back upstream. Poorly sediment loaded water might simply have flowed downstream. It is not clear if the frame weirs were opened. The riverbed downstream of the reservoir appears to be stable. This means that bed load transport into the River Debed was limited. Overgrown stones were discovered, suggesting low bed load transport.

In the event of a flood, the dam at Shnogh reservoir retains sediment, but with limited influence on discharge.

Image 32. Dam at the Shnogh reservoir

It can be concluded that reservoirs helped to retain debris, in the majority of cases without any additional damage. But it is important not to plan any significant construction in the backwater of dams. Sediment retention and therefore riverbed aggradation could result in the flooding of these constructions.

4.4. Hydraulic modelling

Selective hydraulic modelling was applied in an attempt to reproduce the measured discharge peaks and the damage observed in the field. The modelling was carried out using HEC-RAS 6.6.

Data and approach

New elevation models of the river area were used as a data basis. These were developed based on drone flights by Globhe in November / December 2024 (resolution 1m). The models were adjusted with cross-sections collected during the field visit in December 2024. Hydraulic modelling was carried out in 1D without consideration of sediment transport. Separate models were created for the heavily affected sections in Sanahin station and Karkop (see Figure 12). Depending on the ground cover, the following adjusted Manning values (n) were defined in the model for the channel and the left and right bank areas: natural bed = 0.033 (Sanahin station) and 0.029 (Karkop), coarse-bouldered natural bank = 0.04, bushes = 0.067, mixed area of coarse, loose stones and wall = 0.033, village area with obstacles = 0.025, mixed area of vegetation and road = 0.025.

Figure 12 shows the HEC-RAS model set-up in Sanahin station (left) and Karkop (right) – RAS mapper view: blue = river axis, green = cross sections, red = bank lines, turquoise = flow paths. CS 860, Sanahin = cross section at the location of observed damage in the building, with water level 2.5–3m higher than the surrounding ground (see Figure 13 and Figure 14), CS 711, Sanahin = cross section at the destroyed bridge (see Image 33). CS 591, Karkop = cross section at the entrance of the village where holes have been observed in the protection walls (see Figure 15). CS 325, Karkop = cross section of destroyed bridge in Karkop (see Figure 16).

Figure 12. *HEC-RAS model*

Results and interpretation

The cases of Sanahin station and Karkop illustrate how important it is to conduct field inspections and record cross-sections even when high-resolution terrain models are available. In Sanahin station, the left river protection wall was not correctly implemented in the model. In Karkop, holes were discovered in the river protection walls during the field inspection in December 2024. If such information is not taken into account in the modelling process (e.g. as part of a comprehensive post-modelling of the event or as a basis for a hazard assessment), relevant misjudgements may occur.

Sanahin station

There is no hydrological observation station in Sanahin station. The nearest one is in Ayrum. The catchment area of the River Debed in Sanahin station is around 3,200km^2 (87% of the area of the catchment area of the River Debed for the Ayrum hydrological observation station). In Sanahin station, damage and water marks in buildings in the settlement on the left bank of the river reached up to 2.5–3m compared to the surrounding terrain, which indicates the maximum water level during the event (see Figure 13). In the high-resolution terrain model, the river protection walls of the River Debed in the settlement area were not correctly included. This was adjusted as shown in Figure 14. According to the model, the reconstructed water levels can be achieved with free-flowing discharges of around 700–800m^3 (level of energy line).

Image 33. Height of protection wall and damages / proofed water level compared to path on the west bank of Debed river in Sanahin station.

The upper illustration shows the geometry according to the drone terrain model, which lacks important details such as the correct height of the protection wall, buildings, etc. In the lower illustration, the correct height of the protection wall and the buildings have been incorporated (building height in the model represents reconstructed water level due to damage and thus not the real building height).

In Sanahin station, however, there were considerable backwater effects due to the damaged bridge, which increased the water level upstream (see Image 34). In addition, the sediment transport is not taken into account in the modelling. The transported sediment increases the flow area for the same volume of water and reduces the flow velocity. As explained above, the sediment dynamics were important in the event and are also likely to have played a role in Sanahin station, albeit a comparatively small one due to the shallow gradient in the settlement area. Even if the recalculation of the event is difficult due to the dynamic of sedimentation and erosion in the riverbed during the event, it can be concluded for the reasons stated that the proofed water level in Figure 13 was not reached by discharges of 700-800m^3/s but by a smaller peak discharge in the order of around 600m^3/s.

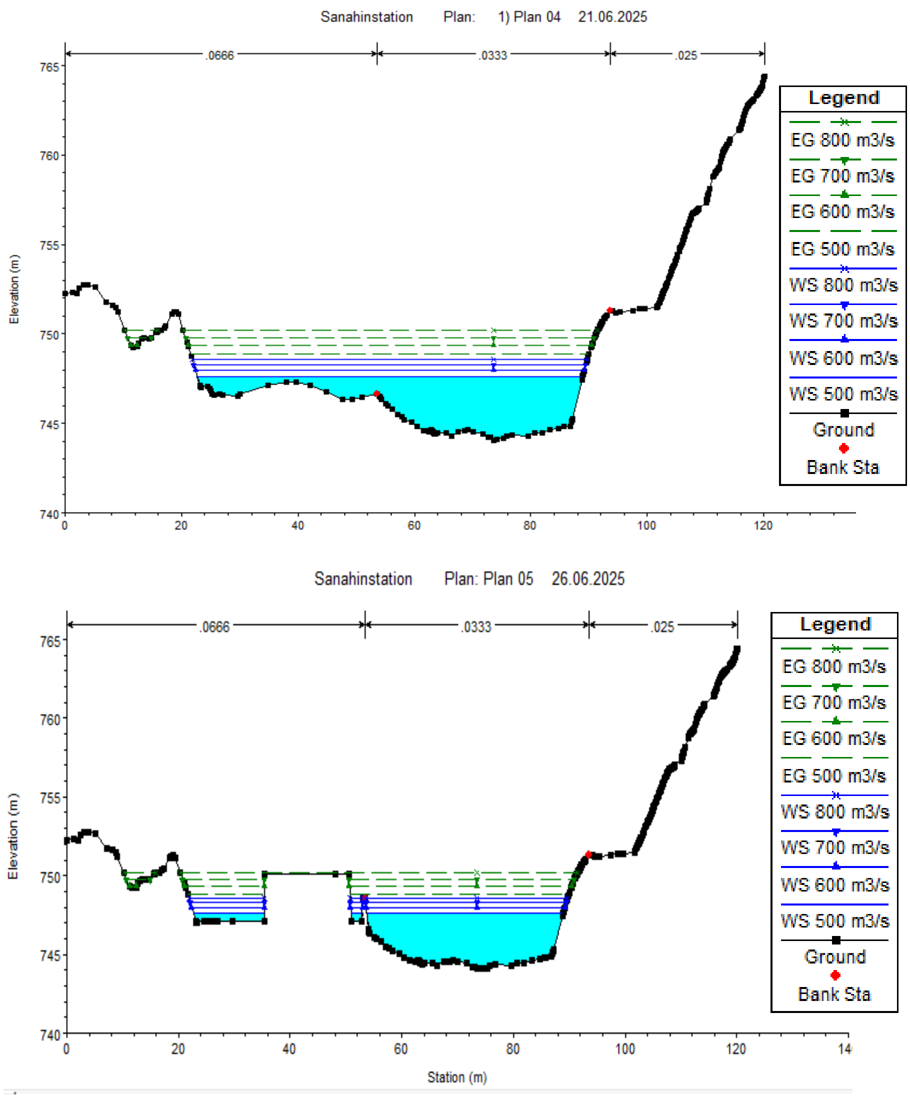


Figure 13-14. Cross section in HEC-RAS model at the location of Image 33.

Image 34. Backwatering effect through damaged bridge in sanahin station:

Karkop

The catchment area of the River Debed in Karkop is 3,660km^2 (99% of the area of the catchment area of the River Debed for the Ayrum hydrological observation station). In Karkop, the holes in the riverbank protection wall played a significant role in the flooding of the southern part of the settlement. These holes were discovered during the field inspection in December 2024 (see Image 7 and Image 8). The geometry in the HEC-RAS model was adjusted so that the ground elevation of the left bank was reduced to the height of the hole. Figure 15 shows that with well-functioning riverbank protection walls, discharges of 800m^3/s would stay within the channel and would not lead to riverbank overflow in this specific cross section at the entrance of the village of Karkop (cross section 591, see Figure 15). Taking the hole into account (node in model 506.10 m.a.s.l.), small water outflows occur from a discharge of 500m^3/s – the energy line is 0.4m higher than the opening of the hole at this peak discharge. For discharges of 600m^3/s, 700m^3/s and 800m^3/s, the water level and the energy line increase steadily (see Table 2) and the water outflow through the hole into the southern settlement also increases. This cross section does not allow an exact recalculation of the peak discharge during the event in May 2024, but it gives a good idea of the minimum peak discharge that occurred in the event.

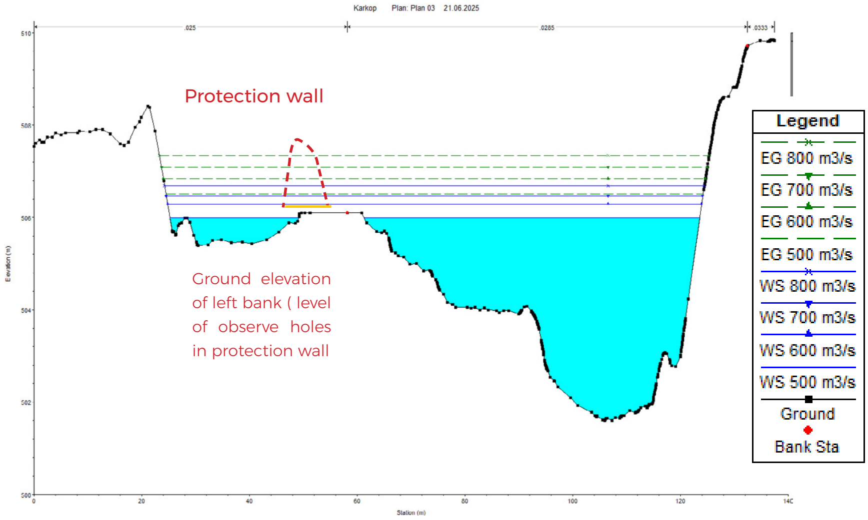


Figure 15. HEC-RAS geometry for cross section 591 in Karkop (southern entrance of the village) including modelled water level and energy line level for discharges between 500-800 m3/s. Geometry of entire cross section induding channel and settlement area. Ground elevation of left bank in model corresponds to level of observed holes in protection wall. Protection wall above the holes was not considered(red dashed line).

Reach	River Sta	Profile	Q Total	Min Ch El	W.S. Elev	Crit W.S.	E.G. Elev	E.G. Slope	Vel Chnl	Flow Area	Top Width	Froude #Chl
				(m3/s)	(m)	(m)	(m)	(m)	(m/s)	(m2)	(m)	
Karkop	590	500 m3/s	500.00	501.6	506.00	505.29	506.51	0.002663	3.19	162.75	86.24	0.65
Karkop	590	600 m3/s	600.00	501.6	506.30	505.67	506.84	0.002646	3.33	191.14	99.14	0.66
Karkop	590	700 m3/s	700.00	501.6	506.48	505.97	507.10	0.002799	3.57	209.07	99.61	0.68
Karkop	590	800 m3/s	800.00	501.6	506.69	506.29	507.35	0.002774	3.71	230.08	100.20	0.69

Table 2. Model results at the cross section 591 (cross section south Karkop with hole in protection wall). Level of hole: 506.1 m a.s.l.

The cross section at the destroyed bridge (cross section 325) also allows conclusions about the magnitude of the peak discharge during the event. According to the modelling, a peak discharge of 500 m^3/s does not lead to riverbank overflow (energy line at the upper edge of the cross section and thus in the area of the former bridge). The water level of a peak discharge of 600 m³/s is still 0.9 m below the upper edge of the left embankment, but the energy line is around 0.7 m above it. At this discharge, water outflows are to be expected. Damages to the former bridge were possible, particularly due to erosion in the canal, which has also been observed in other bridges. The extent of water outflows before the destruction of the bridge was higher, but the exact extent depended on the exact position of the bridge and depends a lot on the dynamics during the event. Peak discharges of 700 m³/s and higher would have led to an overflow of the former bridge and its destruction has to be expected. Based on these recalculations, it is assumed that the discharge in Karkop was at least 600-650 m³/s.

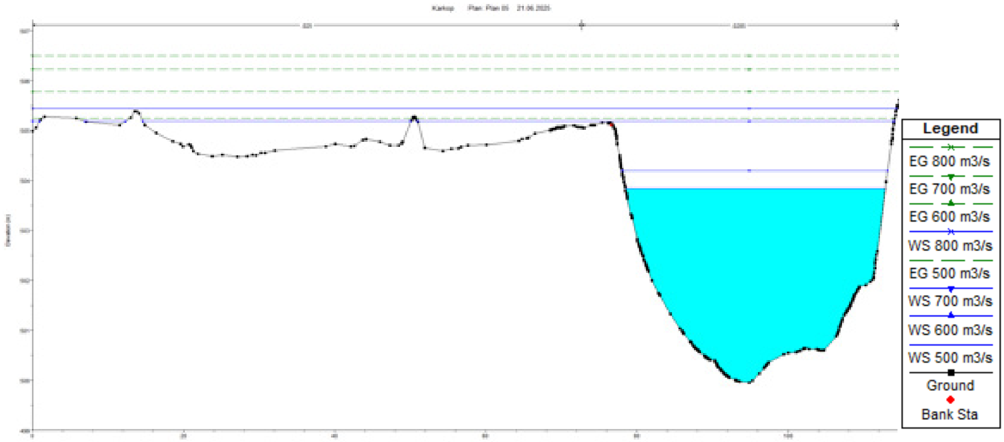


Figure 16. *HEC-RAS geometry for cross section 325 in Karkop (destroyed bridge) including modelled water level and energy line level for discharges between 500-800 m3/s.*

5. Early Warning and Alert System

The May 2024 floods in the Lori and Tavush regions were a stark reminder of the evolving risk landscape in Armenia, shaped by extreme weather events and complex hydrometeorological dynamics. While the disaster inflicted widespread damage, it also catalysed a whole-of-government response and reaffirmed the need for systemic improvements in early warning systems, risk communication, infrastructure resilience, and recovery governance.

The need for institutional modernisation and enhanced preparedness capacities is evident and is addressed widely in the reformation of the DRR sphere through legislative and operational developments. In parallel with the immediate rescue and recovery efforts, a process of structural review and reform has been initiated to ensure that Armenia's disaster risk management system becomes more anticipatory, inclusive, and resilient.[3]

5.1 Early Warning System: Gaps and Ongoing Improvements

From 24 May 2024, the "Hayhydrome" SNCO issued special warnings regarding intense rainfall - an alert message. On 25 May 2024, Armhydromet issued a hydrological bulletin, which was disseminated via its official website and Facebook page. However, the information provided mentioned significant increases in river water discharges, but did not indicate an imminent or extreme flood event, and as a result did not activate any emergency alert systems. This gap between technical forecasting and operational alerting highlighted the need for a more responsive, multi-level early warning system (EWS).

The current system, while functional in terms of data provision, lacks the capability to translate risk information into time-bound, localised, and actionable alerts for municipalities and communities. The experience of May 2024 demonstrated that without integrated protocols and community-tailored dissemination tools, forecasting alone is insufficient to prompt protective action.

5.2 National-level emergency response measures

The government responded rapidly to the disaster through a coordinated multi-agency effort. Key actions included:

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[3] The law of the Republic of Armenia on disaster risk management and civil protection, as at 18.04.2025 (enters into force on 1 January 2027), https://www.arlis.am/hy/acts/206798; governmental decision N1717-L of the Republic of Armenia, on the adoption of the 2023–30 Disaster Risk Management Strategy and the 2023–26 Action Plan, https://www.arlis.am/hy/acts/183691

- The Ministry of Internal Affairs promptly launched search and rescue operations. In total, 1,809 rescue personnel from 136 teams and 42 operative groups were deployed. Temporary pedestrian bridges were assembled in Karkop and Sanahin to restore basic mobility.
- An emergency working group was established by Prime Minister's Decree N 492-A (26 May) to lead the coordination of response and early recovery efforts. Crisis communication was maintained through press briefings and official channels.
- 2,382 people were temporarily evacuated from high-risk zones; 332 individuals stayed with relatives or in six designated hotels, while others returned home.
- Cleanup operations were supported by over 120 staff from the Eco Patrol Service and ArmForest, alongside 2,500 volunteers from academic institutions, state and non-governmental bodies, coordinated by the Ministry of Labour and Social Affairs and the Ministry of Education, Science, Culture and Sports.
- The Armenian Red Cross Society deployed 200 volunteers to assist in rescue and early recovery, distributing 515 hygiene kits in Alaverdi and Karkop.
- 20 volunteers from the Lore Rescue Team NGO participated in search and rescue operations alongside Ministry of Internal Affairs from 26 to 28 May.
- Critical infrastructure was temporarily restored by key operators, including the Road Department (SNCO), Water Users Association, Gazprom Armenia (CJSC), Electric Networks of Armenia, and Veolia Djur (CJSC).
- Damage assessment and compensation commissions were mobilised to gather field data, and non-food items, including hygiene products and clothing, were distributed to affected families.
- These actions highlight the government's capacity for rapid mobilisation and the strong role of civil society and volunteerism in disaster response.

5.3 Coordination and institutional communication

Despite strong mobilisation during the response phase, the event revealed opportunities to strengthen pre-disaster coordination and preparedness mechanisms. Although the task force under the MTAI was swiftly activated, the scale and suddenness of the disaster challenged existing preparedness frameworks, especially at the local level. To improve this dimension, the MIA and partners are:

- developing a national coordination framework for multi-agency and multi-level disaster response;
- institutionalising joint exercises and simulations for municipal authorities;
- revising crisis communication protocols to reduce latency in alert dissemination.

5.4 Infrastructure resilience and restoration

The collapse of a 50-metre section of the M6 highway and multiple bridges over the River Debed underscored the exposure of critical infrastructure to extreme hydrological stress. Contributing factors included the age of the structures, insufficient maintenance, and the lack of risk-informed engineering standards. In response:

- the government has launched rapid technical assessments of critical structures;
- design standards for public infrastructure are being revised to include flood-resilience criteria, especially in mountain river basins;
- longer-term rehabilitation plans are being developed based on multi-hazard risk assessments.

5.5 Post-Disaster Recovery and Social Support

While some targeted compensation was issued (e.g. to vehicle owners), the government acknowledged the importance of a more holistic recovery framework encompassing housing, livelihood restoration, and community rehabilitation. These efforts included:

- field-based needs assessments in the affected consolidated communities (UNDP, 2024a, 2024b);
- provision of essential non-food items to meet immediate household needs;
- engagement with international partners to explore options for emergency cash transfers and livelihood support schemes.

5.6 Legal and Policy Issues: Roadmap for Reform

The current Law on Population Protection in Emergency Situations provides a foundational structure for disaster response, but the May 2024 event highlighted critical areas for reform, including:

- provisions for flash floods and rapid-onset events;
- municipal mandates for local emergency planning and drills;
- integration of scientific and hydrometeorological data into emergency decision-making;
- assignment of responsibility for post-disaster evaluations or institutional learning.

The MIA is coordinating a legislative review process aimed at updating the legislative background to reflect emerging risk patterns and international best practices, embedding early warning responsibilities, scientific integration, and community engagement into legal mandates, and establishing protocols for post-event analysis, data archiving, and cross-institutional learning.

6. Aftermath of the Disaster and Need Assessments

This event analysis does not intend to revise or reiterate the findings of the immediate and post-disaster analyses requested by the government of Armenia and realised by international partners under the lead of the UN Country Team. However, a short overview of the Country Team's findings on the damage is presented here to give an overview of the disaster, the response and the various recovery-oriented analytical tools.

6.1. Disaster impact assessment toolkits for immediate response and recovery framework strategies: MIRA and PDNA.

In response to the severe flooding in Lori and Tavush regions, the Government of Armenia declared the affected areas disaster zones and urgently requested international support. At the request of the Ministry of Internal Affairs, a Multi-Cluster Initial Rapid Assessment (MIRA) was conducted with the support of the UN system, to evaluate immediate humanitarian needs and prioritize life-saving interventions.

This was followed by the PDNA jointly undertaken by the Government of Armenia, UNDP, the European Union, and other international and national partners. The PDNA adopts internationally recognized methodologies to assess sectoral damage and loss, define short-, medium-, and long-term recovery needs, and guide a Build Back Better recovery approach that integrates risk reduction and sustainability principles.

Multi-Cluster Initial Rapid Assessment - MIRA

The MIRA was launched on 30 May 2024, following an official request from the MIA. It was conducted under the coordination of UNDP, in collaboration with specialised UN agencies including UNHCR, UNICEF, FAO, WHO, UNFPA, WFP, and IOM, and in cooperation with national stakeholders such as the MTAI, the former CMSA, and the Disaster Risk Reduction National Platform (DRRNP) of Armenia (UNDP, 2024b, p.2).

The MIRA methodology was in line with the globally accepted Inter-Agency Standing Committee (IASC) Operational Guidance for Coordinated Assessments in Humanitarian Crises, and combined secondary data analysis, GIS-based remote sensing, and community-level field data collection in nine consolidated communities and 39 settlements across Lori and Tavush. These areas were categorised into three damage levels – minor, partial, and significant – based on observed impact (UNDP, 2024b, p.5-6).

Between 4 and 5 June 2024, joint UN assessment teams conducted on-site inspections and interviews using three structured modules: observational site assessments, interviews with administrative representatives, and individual interviews with affected populations. A total of 71 field inputs were collected, including 30 interviews with affected individuals and 16 observational assessments, covering communities such as Alaverdi, Tashir, Noyemberyan, and Dilijan (UNDP, 2024b, p.7-8).

The MIRA findings confirmed the widespread impact of the flood disaster:

- 40,839 individuals were affected, with 2,382 people evacuated, and 464 dwellings damaged or destroyed.
- Refugee populations in Tashir and Alaverdi faced compounded vulnerabilities, including the loss of shelter, food stocks, and access to basic services.
- Critical infrastructure, including 24 major bridges, 41.8km of roads, 3.3km of embankments, and hydropower plants were severely damaged (UNDP, 2024b, p.9-11).

The MIRA served as the foundation for Armenia's PDNA, initiated shortly after. It helped identify priority actions for emergency response and guided the mobilisation of international support. For example, it informed the deployment of the Swiss Rapid Response Team, UNOSAT remote sensing missions, and the EU Civil Protection Mechanism, which provided structural engineers, modular bridge designs, and satellite imagery (UNDP, 2024a, p.28-29).

Importantly, MIRA confirmed that the initial impact extended beyond physical infrastructure, affecting mental health, livelihoods, and community cohesion. Psychological stress among displaced populations, especially children and female-headed households, was highlighted as a major concern. These insights contributed to a cross-cutting emphasis on protection, mental health and psychosocial support (MHPSS), and gender-sensitive recovery planning (UNDP, 2024b, p.12-15).

It should be acknowledged that MIRA was not only a rapid response tool, but also a strategic enabler of long-term recovery planning. It exemplified the importance of coordinated, data-driven, and locally adapted humanitarian assessments, ensuring that emergency actions were aligned with the actual needs on the ground. Its findings directly shaped the scope and structure of the PDNA and reinforced the value of multi-sectoral disaster response preparedness in Armenian national resilience strategy.

Post-Disaster Needs Assessment - PDNA

As already noted, in the aftermath of the floods, the government of Armenia also launched a comprehensive PDNA to quantify the impacts, assess sectoral losses, and define the recovery and reconstruction framework. This assessment was conducted in close collaboration with the United Nations Country Team (UNDP as the lead coordinator), the European Union, and other international and national stakeholders, following globally recognised PDNA methodologies.

The PDNA was critical in transforming the initial response findings from MIRA into a quantified analysis of damage, losses, and needs across multiple sectors.

- USD 127 million in total effects, including USD 60.5 million in damage and USD 66.6 million in economic loss.
- Impacts on over 40,000 people, with 2,382 individuals temporarily evacuated and nine major communities directly affected.

- 25 homes damaged beyond repair, 244 homes with significant damage, destruction of transport infrastructure, collapse of multiple bridges, and disruption of electricity, gas, water supply, and communication lines.

The assessment covered 15 sectors, including housing, education, health, agriculture, water and sanitation, energy, environment, transport, commerce, and disaster risk management. Each sectoral report quantified damage and losses and proposed costed recovery requirements categorised into short-term (0–12 months), medium-term (1–3 years), and long-term (3–5 years) horizons.

So far, the assessment reports identified the following main damage and losses:

Human impact:

4 casualties
2,382 persons temporarily evacuated
40,839 people affected

Housing:

25 dwellings damaged beyond repair
244 dwellings with significant damage
155 family houses and 114 apartments affected
Total of 22,058m2 floor area affected

Agriculture:

24 irrigation assets (3,587m of pipelines / channels and 43 pumps / stations)
162 ha. of land washed away
84 ha. of perennial crops affected
43 ha. of crops no longer viable (due to irrigation loss)
304 ha. of high-value and 310 ha. of low-value annual crop land flooded
Livestock significantly reduced
8 aquaculture facilities damaged (6.7 ha.)

Business:

2,100 jobs lost
149 businesses affected
46% of all damage related to buildings, 35% to production lines, equipment and tools, and 18% to goods in stock

Community infrastructure:

45% of affected communities experienced full communication outages
6,074 metres of gas pipes partially damaged
Power transmission lines, transformers, and electric stations were damaged
680 metres of sewage pipeline were affected
4,090 metres of drinking water pipeline were partially or totally damaged
In the health subsector, one medical facility and two pharmacies were affected
In the education subsector, one school and pre-school damaged

Transport:

National highway M6 damaged at 30 sections (total 7.1km)

National highway M4 damaged at 10 sections over an 11km stretch
2km of railway track disrupted at several locations over a 50km stretch
4 bridges over the River Debed connecting settlements with the M6 collapsed
7 smaller bridges and 8 drainage structures destroyed / damaged
20 footbridges destroyed / partially damaged
161 vehicles damaged/destroyed

Disaster risk reduction:

2,300 volunteers participated in cleanup actions
1,997 employees conducted rescue operations
8 hydrological observation stations damaged
1,677m of retaining walls damaged on the M6 and 1,156m in the Alaverdi, Tashir and Dilijan communities

Environment:

Volume of eroded riverbank is estimated at 422,242m3
Volume of removed trees is estimated at 594m3 (2,969 trees total)
Surface of soil, mud, wood and metallic deposits: 142.7 hectares

In conclusion, each of the above-mentioned toolkits was crucial for understanding the impact of the disaster as well as the requirements for the due planning and efficient realisation of recovery policies. These instruments provided the government with complementary, participatory and supporting materials for future policies and were aligned with the Sendai Framework and Sustainable Development Goals (SDG), and hence based on the principles of leaving no one behind and building back better.

6.2. Earth Observations and Remote Sensing

In response to the international request for assistance extended by the Republic of Armenia, the European Union Civil Protection Mechanism's (UCPM) Emergency Response Coordination Centre (ERCC) was activated, and the relevant analytical instruments were triggered (Figure 16). The International Charter: Space and Major Disasters (Disasters Charter) was also activated under the call 'Flood in Armenia – 886 (Call-1013)'. As part of this initiative, over 60 high-resolution satellite images of the affected area have been provided since 29 May 2024. The most informative images were selected for the analyses. Remote sensing and spatial imagery analyses were conducted both by experts from the former CMSA and by participating organisations of the Disaster Charter, including Airbus (France) and RADARSAT (Canada).

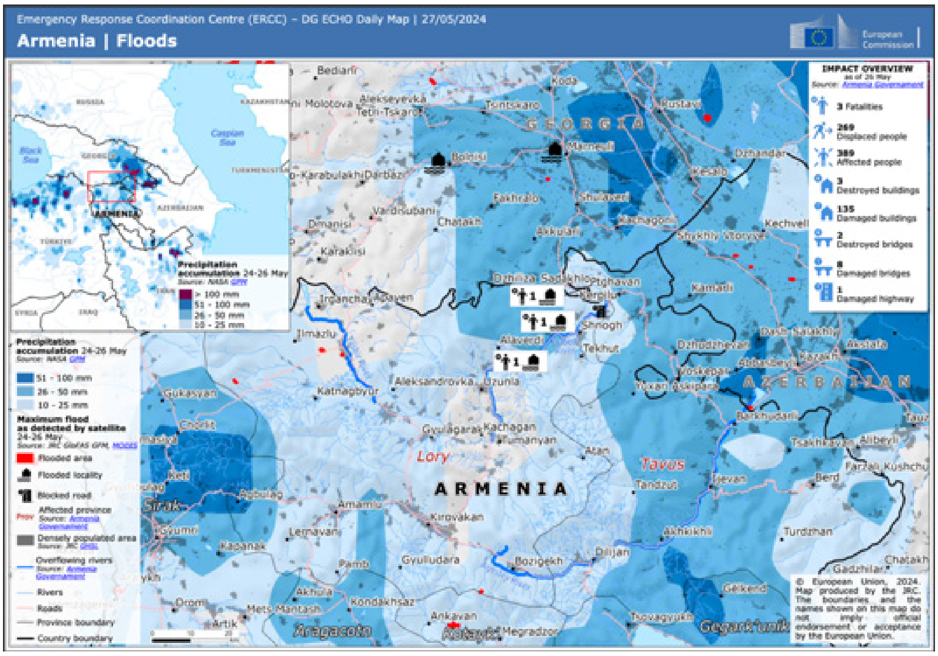


Figure 17. *Situation Map for Armenia Floods as of 27.05.2024.*

Additionally, an analysis of the flooded areas was conducted by the International Science and Technology Center (ISTC) using comparative imagery to illustrate pre-flood and inundation-phase conditions of the river basins within the disaster zone (Image 35 - Image 44).

The satellite images were obtained from Planet's PlanetScope satellite. These data served as the primary source for determining the extent of the flood. The images were captured on 28 May 2024. This analysis focused on the Debed river basin, which caused the most significant damage.

The extent of damage along the riverbanks was analysed through remote sensing by the ICube-SERTIT emergency response service. The SERTIT team provided a localisation, qualification and quantification of debris along the River Debed (UNDP, 2024a, p. 109-110, 113).

Image 35. Ayrum Settlement Area: April, 2023. (comparative)

Image 36. Ayrum Settlement Area: May 28, 2024 (flooding)

Image 37. Shnogh Settlement Area: April 2023 (comparative).

Image 38. Shnogh Settlement Area: May 28, 2024 (flooding)

Image 39. Akhtala Residential and Industrial Areas: April 2023 (comparative).

Image 40. Akhtala Residential and Industrial Areas: May 28, 2024 (flooding)

Image 41. Alaverdi Settlement, Bridges: April 2023 (comparative).

Image 42. Alaverdi Settlement, Bridges: May 28, 2024 (flooding)

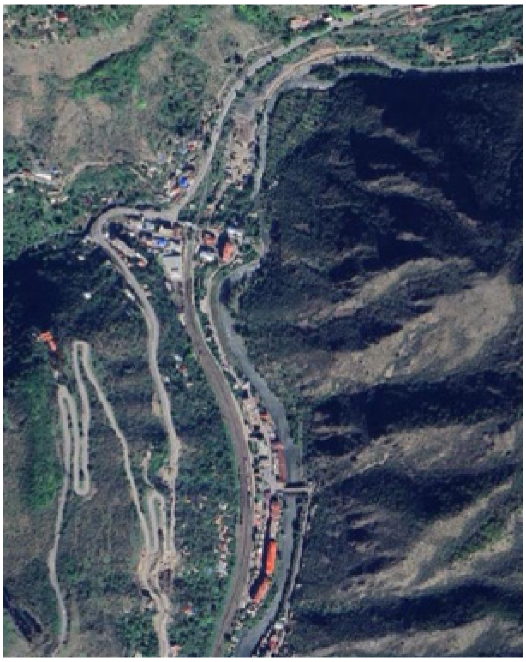


Image 43. Alaverdi Southern Area: April 2023 (comparative).

Image 44. Alaverdi Southern Area: May 28, 2024 (flooding)

6.3 Additional post-disaster risks revealed

The aim of the flood and multi-hazard risk analyses was to provide decision-makers with a comprehensive overview of the disaster impact and potential additional risks in the area (see Figure 18 and Figure 19) (Copernicus EMS, 2024). These analyses were conducted using earth observation (EO) techniques supported by remote sensing platforms and specialised EO toolkits such as the ones provided by PlanetScope, RADARSAT, and the Disasters Charter.

Alongside the damage assessment activities, it was important to take into account that the affected territory included active mudflow zones and landslide-prone areas. Should they be triggered by additional rainfall or other contributing factors, further damage to the impacted communities might occur.

On behalf of the authorised user – the MIA – we requested an additional analysis on the possible activation of landslides in the affected zone. Two areas of interest in the flows of the Debed river basin were chosen as the most vulnerable areas. The results of the remote sensing analyses were very important for future decision-making, as they showed the landslide-prone areas, which had already suffered from the flooding.

Detailed interpretation concerning each settlement and infrastructure can be realised based on the acquired information.

Event Type
Mass movement

Affected Countries
Armenia

Event Time
2024-05-26 12:00 UTC

Activated by
DG ECHO
on behalf of Ministry of Internal Affairs of the Republic of Armenia

Last Update
2024-06-06 15:14 UTC

Activation Extent

Activation Reason

Starting from 26th of May 2024, heavy rainfall and consequent floods hit northern Armenia, particularly Lori and Tavush Provinces, causing casualties. Hundreds of people experienced power cuts, and almost 17 bridges have been destroyed. The CEMS Risk and Recovery Standard has been requested to provide a landslide risk assessment in the northern regions of Armenia affected by this event.

Delivered Products

Preparedness

ID	Name	Scale
P17	Landslide risk assessment	1:25000

Figure 18. *The areas of interest requested on behalf of the Authorized User (MIA): landslide.*

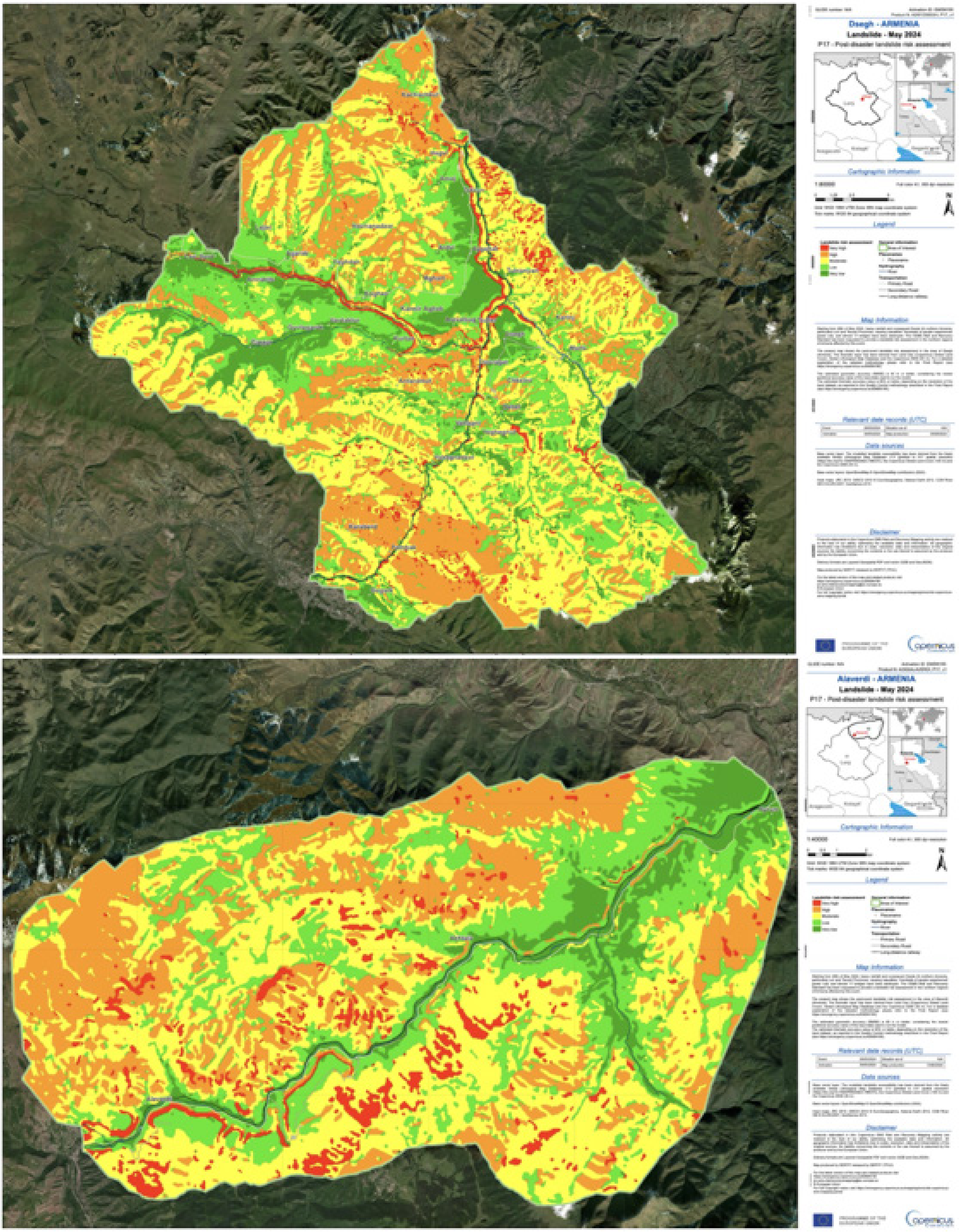


Figure 19. *Outcomes of the AOI1 and AOI2 studies: landslide.*

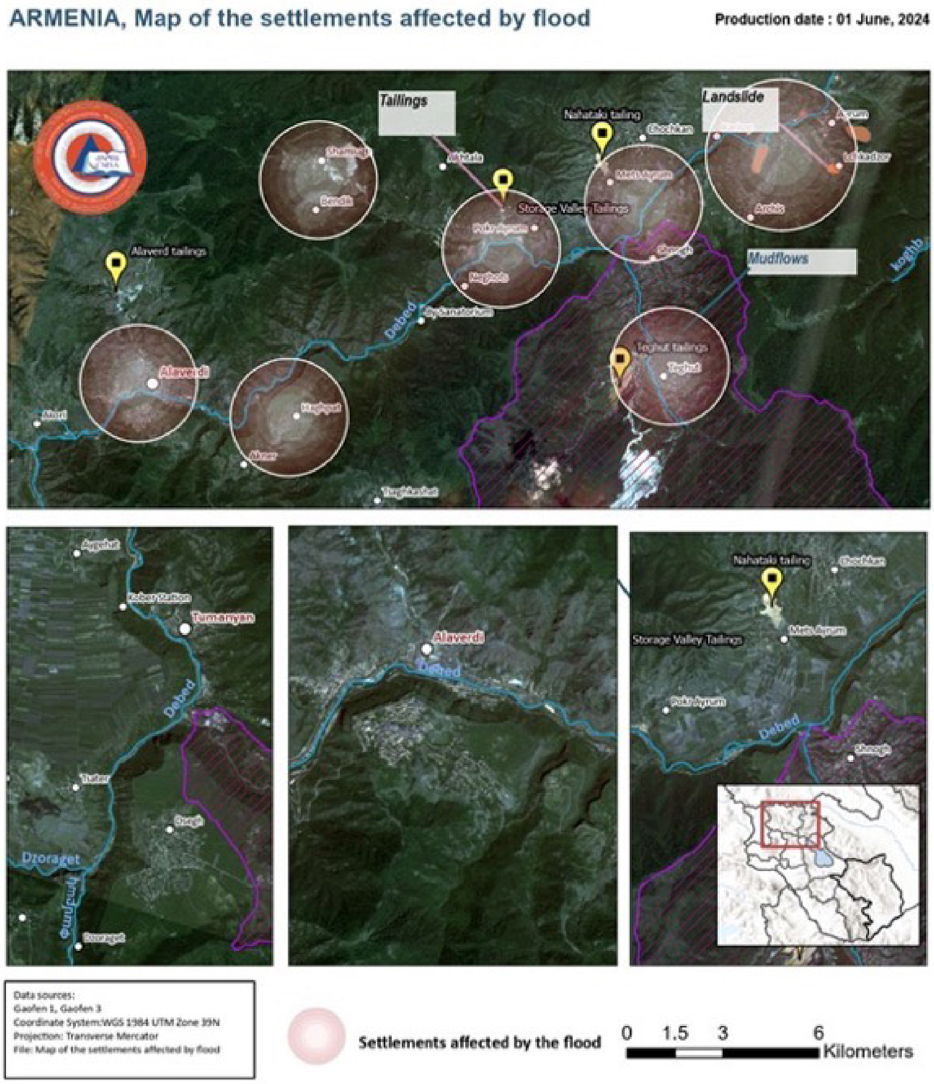


Figure 20. *Settlements affacted by the floods and the potential additional risks.*

The Imagery from the GAOFEN-1 and GAOFEN-3 satellites acquired due to the Disasters Charter activation: allowed realizing certain risk assessments for the settlements in the Debed River flow.

1. So far, the areas around Ayrum, Lchkadzor, Archis, and Karkop included active landslide-prone zones (highlighted in red in Figure 20). The potential reactivation of these zones posed serious risks to the nearby communities and vital infrastructure located within these areas.

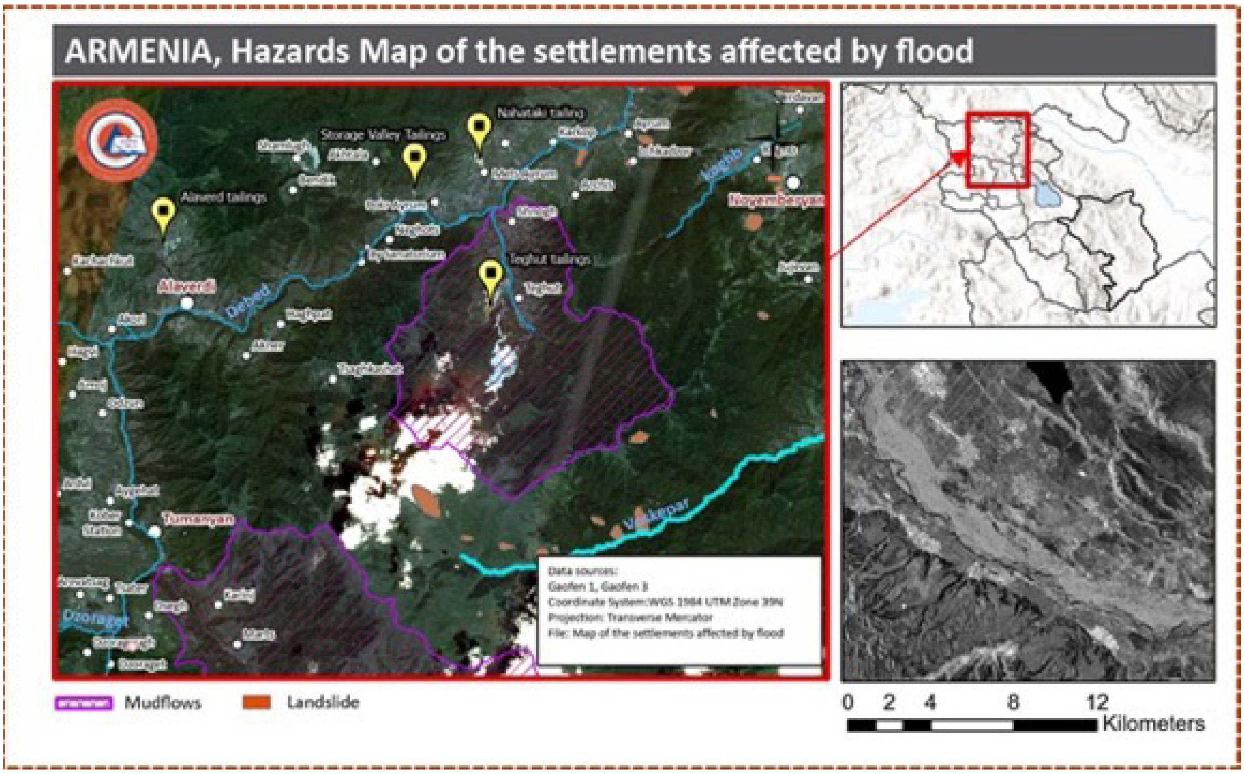
2. Northwest of Mets Ayrum and Pokr Ayrum, there are both decommissioned and active tailings dams (notably the Nahatak tailings facility). Ensuring their stabilisation, safe management, and environmental restoration is a top priority not only for the residents of these villages, but also for other communities located downstream in the river basin.

3. The Alaverdi tailings dam, situated north of the town of Alaverdi, likewise required urgent assessment and continuous monitoring, as do all other active and conserved tailings sites in the region.

4. The villages of Shnogh and Teghut are located within a high mudflow risk zone (shown with purple crosshatching on Figure 21). In addition, the village of Dsegh, though not inside the designated mudflow zone, lies immediately south of it. Given this proximity, potential sec-

ondary impacts from mudflows should not be neglected for Dsegh either.

5. The composite risk map presented below clearly indicates that a set of integrated DRR measures or, at the very least, regular monitoring must be undertaken to ensure the safe and sustainable recovery of flood-affected communities. These actions should be based on localised, settlement-specific risk analyses, tailored to the unique vulnerabilities and hazards for each **community.**



Data sources:
Gaofen 1, Gaofen 3
Coordinate System:WGS 1984 UTM Zone 39N
Projection: Transverse Mercator
File: Map of the settlements affected by flood

Figure 21. *Settlements affected by the flood and the additional possible risks.*

6.4 Field data collection, photo documentation and photogrammetry

In parallel with disaster response and early recovery operations and the above-mentioned rapid assessment missions, documentation and data collection was carried out by the team of volunteers from the former CMSA, led by UNDP specialists.

The records of the field observations journal convey some first impressions in the assessment process:

“Date of visit: 4 June 2024
Region: Lori and Tavush provinces, Republic of Armenia
Settlements visited: Gyulagarak, Gargar, Tashir, Akhtala, Alaverdi, Karkop, Sanahin
Event: Consequences of the 26 May 2024 flood

On 4 June, after floodwaters began to recede and roads reopened, we set out for the first field mission to the village of Gyulagarak. With its neighbouring village of Gargar, Gyulagarak lies in the lowland areas along the River Gargar. The greatest destruction here occurred at the pe-

destrian bridges connecting the residential part of the settlement to the pasturelands. These bridges were vital for local farmers and herders to move livestock.

The inability to access their animals represented not just a financial threat, but also an emotional burden. Livestock are deeply tied to household income and mean a lot to the family in these communities.

The destruction of the bridges was caused by a powerful surge of water from the mountains, which brought with it large debris – logs, boulders, and mud. The bridge supports had been set directly in the riverbed and were not sufficiently reinforced or protected against erosion. As the current intensified, it undermined the foundation, leading to collapse. Some components showed signs of lateral displacement, indicating that the water's horizontal force was also significant.

In the second half of the day, we surveyed damaged areas in the town of Tashir. A clear psychological divide was observed among residents, depending on their location:

- The right bank, which is more elevated, underwent moderate flooding – up to 0.5 metres. Flooding mostly affected basements and ground-level storage areas. Residents were obviously concerned, but calm. They wondered about possible compensation.
- *The left bank, which is significantly lower, bore the real impact of the disaster. The water level reached 1.5 metres and more, submerging ground floors of houses and damaging vehicles. The atmosphere here was one of fatigue and uncertainty. People asked the same pressing question:* ***Will there be aid – and how can it be accessed?***

At the time of our visit, no official information about compensation procedures had been communicated to the residents. We conducted in-person interviews, documenting the extent of damage, property loss, and urgent needs."

All the collected data and photo materials were systematised, and provided to the MIRA and PDNA assessment teams for future analyses if needed. These photo materials, with geopositioned data, reflect technical aspects of the disaster damage and illustrate some interesting aspects:

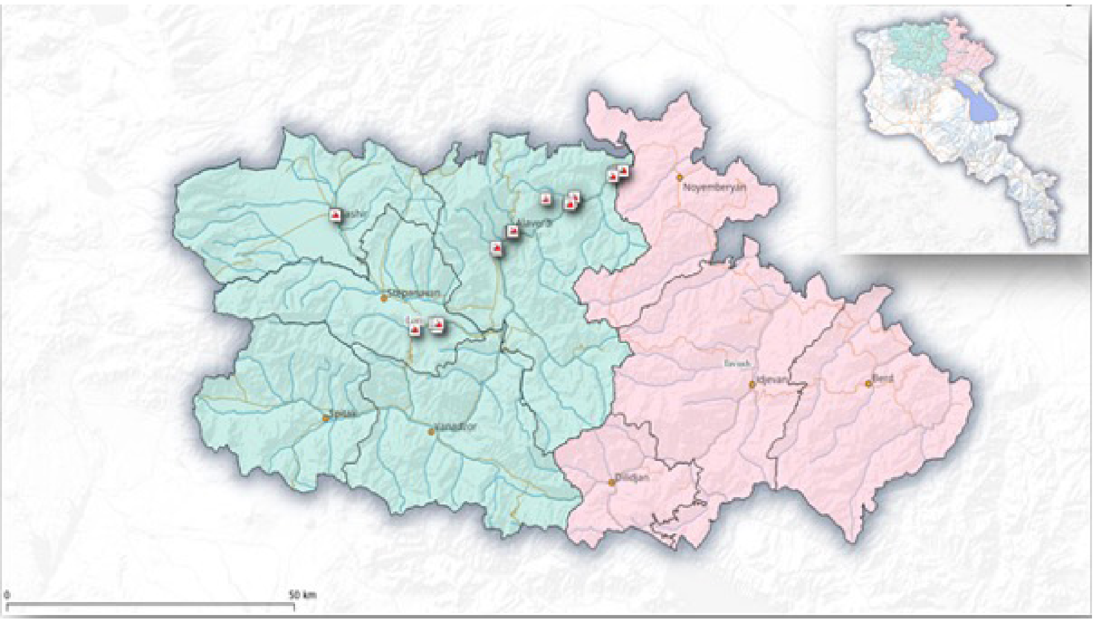


Figure 22. *Photo-documentation / mapping at most damaged locations.*

1. The locations of the affected households and infrastructure can be immediately determined from the photos, enabling a quick overview of the affected zone on the map (Figure 22).

2. Technical damage to physical assets can have forensic value, showing the level of vulnerability of the object with and without the impact of the disaster. These analyses outline the state, technological characteristics, pre-disaster condition and other features exacerbating the level of damage caused by the natural event, which resulted in disaster because of inadequate preparedness and the lack of resilience of the given asset.

3. Most of the observations indicate that infrastructure is in a very poor and outdated state. In the case of housing, the most damage caused was often to early 20th century buildings, wooden floors/walls and fragile structures, as well as improperly built, unauthorised, low-cost buildings, stores, and household structures for cattle or animal husbandry built in the river flow area. In other cases where the level of water exceeded 2.5 metres, flooding the first floors of multifamily residential stone buildings, the level of damage is not as critical as in the previous case. Here the damage caused was mostly to furniture and household equipment, which is potentially of high value. However, after a certain amount of reconstruction work, the buildings could be made fit for use.

4. Concerning community infrastructure and bridges, here the above-mentioned criteria also apply in terms of initial engineering mistakes or improper design. The medieval bridges provide an excellent comparison to the assessments expressed above. Despite being on the same river, they were not affected, while the modern ones were totally destroyed.

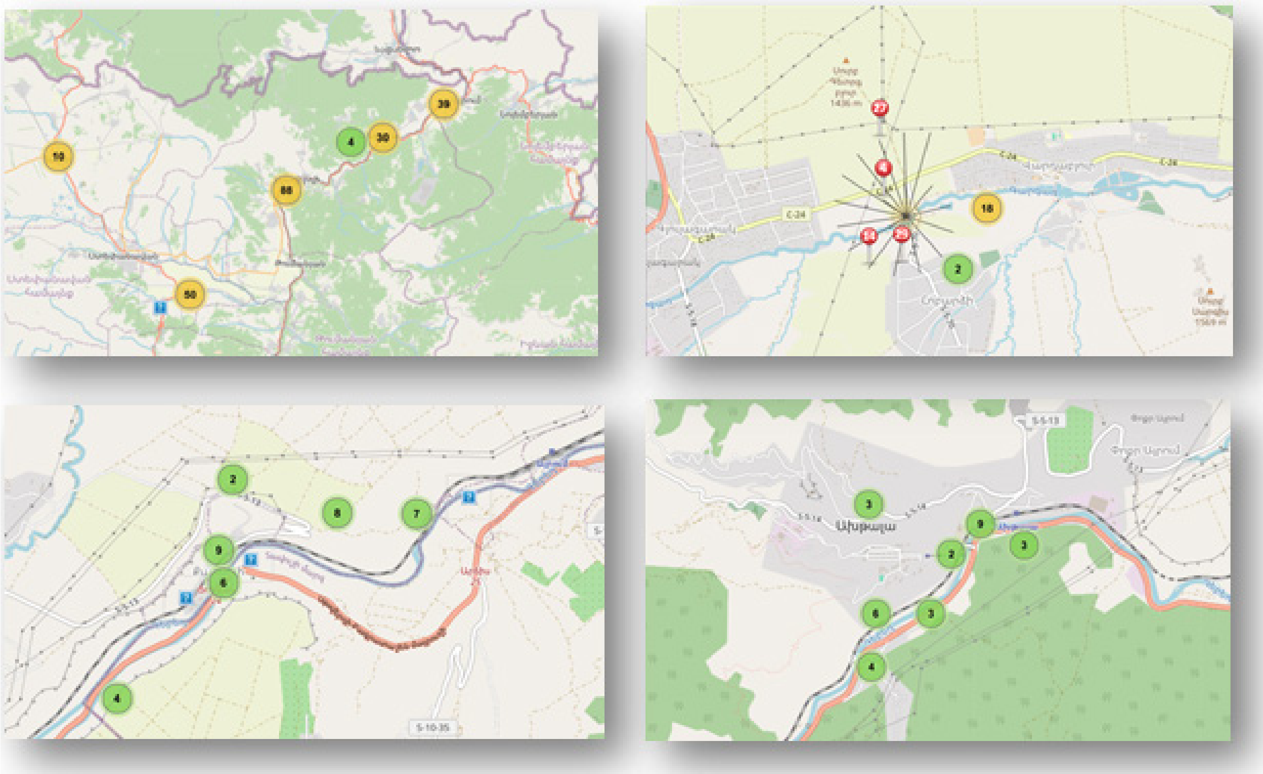


Figure 23. *Examples of points of observation.*

Akhtala

Sanahin

Alaverdi

Tashir

Image 45. Examples of observation points.

6.5 Innovative solutions for disaster documentation

In order to better understand the destruction, its characteristics, a large variety of aspects that cannot be observed at the first attempt due to various reasons – shortage of time, resources, accessibility etc., field precise documentation methods are being used in various spheres, usually more related to cultural-historical observations rather than disaster impact documentation.

However, using modern technologies like unmanned aerial vehicles (UAVs or drones as they are mostly referred to) or any other device that can help realize a remote footage of the area of physical destruction we photographed and created digital models of two bridges in the flood affected zone. These were the bridges of Hobardzi and Gargar both on the river Gargar, with certainly varying features and characteristics for better comparisons and model-testing.

The most important aspect in this method while documenting the damage caused by the disaster is its precision and hence, reliability.

The field footage process that lasted less than 30 minutes, which was the maximum possible flight for the DJI Mavic 2 drone (because of battery shortage) and a couple of hours of processing yielded the initial model that could be measured and observed at its most inaccessible angles and positions. Inaccessibility and impossibility in case the observations be made physically on the ground are no more relevant in most cases if the object is visible and reachable for the UAV.

The technical characteristics of the model (point clouds and triangulation of all points) allow measuring each point of the model for its geological position and absolute elevation, working with digital elevation models, understanding declines, angles, distances from the least to the farthest detail.

In the process of this event analysis series of such models could become the best information source for physical damage assessments. At least, as a scientific approach, this one, hopefully will become a regular tool in documenting and understanding risk for its multiple benefits:

- Saving time and resources (one person – cameraman/drone operator)
- Possibility of future analyses and discussions with other engineers and technical specialists, that could not be present in the field
- Absolute level of detailing (depending on resolution – to millimeters)
- Creation of databases of similar events
- Clear and precise evidence for decision makers, analysts and researchers.

The implementation of such a tool for documentation of various disasters in the nature or in urban areas, even for road accidents can critically reduce the time for such processes and drastically augment the quality and reliability of the obtained information, which is essential for the rapid response, forensic aspects in understanding the event and for educational matters related to investigations and their practical implementation.

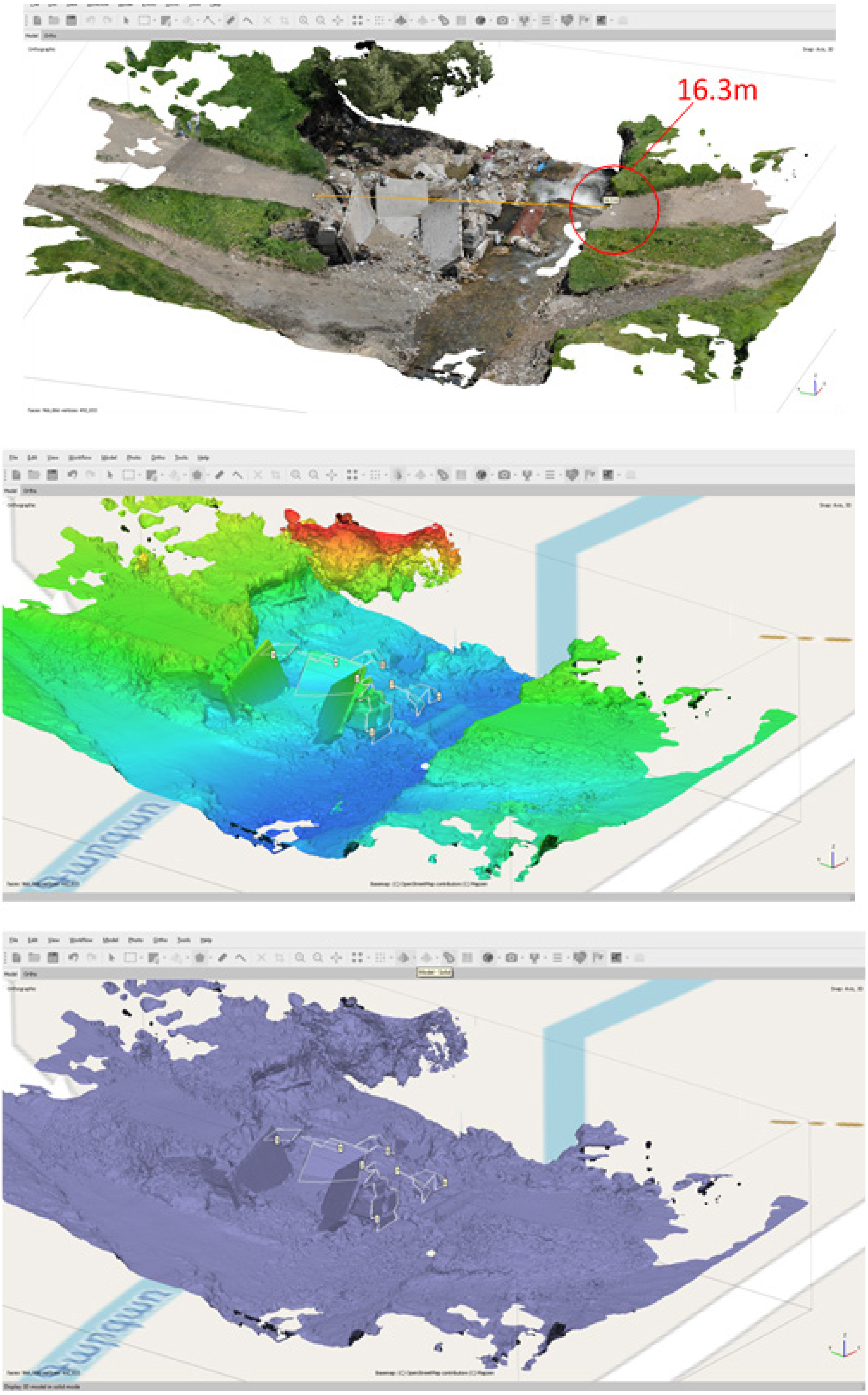


__Figure 24.__ 3D model of the Gargar pedestrian bridge with measurement tool, the DEM model and the solid view.

Figure 25. *The 3D model of Hobardzi bridge.*

7. Conclusions and recommendations:

7.1. Conclusions

This attempt of the flood analyses might possibly go beyond its today's findings, in order to more systematize the assessment toolkits and various approaches both from academic and risk reduction points of view. However, it should be clearly mentioned that no matter which exact paths our investigations go, the aim should be the same: to learn from, be ready to change and be consistent.

The main conclusions the authors would like to outline are as follows:

- On 26 May 2024, floods were caused by heavy rainfall events, affecting a significant area of the Debed river basin, as well as by rainfall events observed during the preceding two days.
- Daily precipitation was not unusual at individual stations, but when considering 3-day entire area total precipitation (from 24 to 26 May) over Debed river basin, the precipitation was a very rare event.
- No snow cover was observed at the meteorological stations from 24 to 26 May, and during May as a whole. April was extremely warm and dry, which led to depletion of snow accumulated during winter months over mountain areas. Therefore, there is very low indication that there was an important snow cover that could affect the discharge in a significant way.
- The event was larger in the Debed River than in the Aghstev River.
- High discharges were accompanied by significant sediment transport, which likely contributed to riverbed elevation, infrastructure blockages, scouring, and channel instability.
- Many damages were caused by the following defects:
    - Inadequate maintenance of walls, which made it easy for the river to enter pre-existing holes or erode deteriorated material, causing the wall to collapse.
    - Unfavorable alignment of the river's water flow due to old structures that diverted the water to the side wall, causing it to erode.
    - Generally weak foundation of protective structures, which allowed undercutting

  - insufficient foundation of the bridge pillars, which were undermined, causing the bridge to become unstable and in some cases collapse.
  - Generally, construction in flood-prone areas resulted in high damages and should be prohibited. Otherwise, it would need to receive special protection (object protection).

- On May 25, a forecast was issued indicating a significant increase in river discharges in Armenia, but no forecast or warning was issued for floods of such magnitude. Therefore, the current hydrometeorological monitoring system and forecasting capabilities of floods and flash floods in Armenia need to be improved. At the moment of the floods, the observations at the hydrological stations were carried out with mechanical instruments in a two-times interval (at 08:00 and 20:00), while maximum levels and discharges may occur outside these observation hours, as in the case of floods of 26 May, 2024.
- On the basis of hydraulic modelling, it was possible to reproduce the water levels during the 2024 floods for specific sections. The order of magnitude of the measured discharge can be confirmed. But the modelling also shows that the observed damages and water levels can be reproduced with discharge volumes that are lower than the measured values - due to backwater effects, sediment transport, etc. Important modelling findings were only possible thanks to the field inspection (recording of cross sections, understanding of flow paths and process dynamics in the event, etc.).

The floods of May 2024 served as an alerting signal to verify the level of Armenia’s preparedness to natural, unusual and unexpected events that may occur more frequently considering climate change and other emerging challenges. Therefore, the most important conclusion is to learn at the highest possible level from disasters, using the ultimate technological and expert capacities around and to transfer this knowledge forward, to better prepare and organize for disaster risk management.

7.2 Recommendations

Based on the findings and conclusions, the following recommendations can be made for reducing flood risks in Armenia:

7.2.1 Hydrometeorological monitoring: modernisation and capacity building

Upgrading the observation system infrastructure and instruments:

- Install automatic hydrological stations measuring water level, temperature (air/water), and precipitation with real-time data transmission.
- Integrate radar/automatic level recorders into a centralised, online data-processing and early-warning system.
- Upgrade existing hydrotechnical structures (cableways, bridges) at observation points.

- Regularly calibrate current meters and relocate hydrometric stations where necessary for improved data quality.
- Acquire appropriate tools and equipment for conducting route snow measurements and restore route snow measurement operations using both ground and remote sensing data (e.g. satellite snow cover).
- Install state-of-the-art weather radar systems (especially dual-polarisation radars) to better capture the spatial pattern and intensity of orographic precipitation.
- Enhance meteorological networks, particularly in high-altitude and mountainous areas, where the observational network becomes sparse and orographic precipitation events are underrepresented.

Establish forecasting systems and models: predictive tools and real-time hazard anticipation

- Implement high-resolution numerical weather prediction (NWP) models with a spatial resolution of 1–3km for forecasting extreme weather events such as heavy precipitation leading to floodings.
- Couple NWP models with hydrological models for real-time flood forecasting.
- Conduct atmospheric sounding observations to better predict convective precipitation.
- Acquire, localise, and implement modern hydrological forecasting models at Armhydromet, including flood prediction, and organise necessary training courses.
- Additionally, high-resolution numerical weather-prediction models need to be used in operations at Armhydromet, as global coarser resolution models are not capable of adequately forecasting orographic precipitation enhancement over mountain terrain, especially in the cases of heavy and extreme precipitation events.

Develop hazard-prevention capacities: policy, planning, and infrastructure

Land-use policy, structural safety, and DRR education

- Develop and apply multiple hazard maps at the basin level, integrate them into early warning and land-use planning tools.
- Adopt and enforce zoning regulations/laws based on the hazard maps that prevent construction in flood-prone areas. It must be ensured that the relevant laws are enforced, followed, and their implementation monitored by a responsible institution at all political levels.
- Provide funding and engineering support for the reinforcement or relocation of at-risk infrastructure (e.g. bridges, retaining walls).
- Introduce courses in fluvial geomorphology, hydraulic engineering, and sediment transport modelling.
- Support transdisciplinary collaboration between hydrologists, engineers, disaster managers, and local governments.

7.2.2 Institutional coordination and operational sustainability:

Governance, budgets, inter-agency cooperation

- Develop an annual hydrometeorological yearbook with evaluated data, analyses, trends, and anomalies (also available digitally).
- Establish an institutional knowledge-sharing platform (intranet, forums, or annual conferences, field excursions) for national and international partners.
- Strengthen inter-agency coordination protocols, especially between Armhydromet, the MoE, crisis management agencies, local governments, and academia.
- Adopt open-data policies for hydrometeorological and non-sensitive geospatial data to foster research and innovation.
- Create a centralised decision-support system integrating risk indicators, hydromet data, and vulnerability maps.
- Ensure stable annual funding for the maintenance and reliable operation of automatic hydrological and meteorological stations.
- Secure consistent funding for the continuous training and professional development of Armhydromet staff.

7.2.3 Data science, evaluation, and learning

Analysis of impacts, failures, and performance:

- Implement a post-event forensic analysis protocol for all major hydrometeorological disasters to trace failures, identify thresholds, and inform model calibration.
- Develop automated real-time dashboards (based on AI/ML tools) to detect anomalous hydromet patterns, allowing predictive alerts.
- Launch a national geodatabase of flood events, linking meteorological, hydrological, economic, and social impact data (with timestamps and georeferencing).
- Conduct multi-hazard correlation studies, especially between snowmelt, rainfall intensity, land cover, and sediment load.
- Establish impact evaluation mechanisms to measure warning effectiveness, forecast accuracy, and post-disaster response time.

Community engagement and strategic integration: public awareness, education, and national policy alignment

- Institutionalise ‘after-action reviews’ (AARs) and ‘lesson-learned’ workshops at national and regional levels, to be conducted after each significant event.
- Document and publish case studies of good practices and failures from the May 2024 floods and prior events.
- Incorporate community-based knowledge and local observations into flood response planning and early-warning messaging.
- Create simulation-based training programmes for municipalities and schools on flash flood behaviour and protective action decision-making.

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