Extreme Events in the Alps Under the Influence of Global Warming - Current Developments, Challenges and Strategies

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INTRODUCTION – ALPINE ENVIRONMENT UNDER THE INFLUENCE OF SOCIETAL CHANGE AND GLOBAL WARMING

The Alpine area in Austria is much more affected by the effects of societal change and global warming than other European regions. With regard to the effects on natural hazards and associated risks, the following megatrends are emerging, which will drive and influence the evolution of disaster risks over the coming decades:

- ✓ *Alps under global warming and extreme events:* retreat of glaciers and permafrost, changes in precipitation patterns (increasingly heavy rainfall, also up to high altitude), extreme flash-floods, debris flows and mass movements, partly triggering cascading events, increase of wildfires, storms, droughts, forest pests
- ✓ *Alps under societal change:* dynamic demographic change, increasing disparities between urban central and peripheral rural areas, regions with economic growth vs. regions with depopulation, increasing vulnerability and decreasing risk acceptance of society
- ✓ *Alps under risks risk-inducing evolution:* resilience deficits in settlement area and critical infrastructure (mobility, energy supply, information technology), competing land-use claims vs (strict) nature conservation (green care), (over)tourism vs preserving traditional ways of life, unlimited transit traffic vs traffic calming and limitation, spreading soil consumption vs de-sealing of soils, agricultural decline

All these trends pose new challenges to Austria′s existing, generally highly effective protection systems for alpine natural hazards and require a reassessment of hazard evaluation. In particular, hazard scenarios must be revised in light of changes in the intensity and frequency of extreme events taking into account emerging multiple (complex) risks scenarios, and protection objectives must be derived accordingly. In this context, the analysis of past catastrophic events and the derivation of general strategies are particularly important. In some cases, it will also be necessary to discuss the "limits of technical protection" and the application of other safety concepts for natural hazards.

IMPACT OF GLOBAL WARMING ON EXTREME EVENTS IN THE ALPS

Austria has warmed by approximately 3.1 °C since the pre-industrial period (1850–1900), with the rate of warming accelerating markedly since the 1980s. The Alpine region is among the areas of Europe experiencing particularly strong warming. (APCC, 2025) The effects of this climate-driven warming include more intense heavy rainfall events with local impacts, increased snowmelt (and a combination of both) and changes in glacier melt. Flood events in alpine regions are increasing in frequency and intensity. Sediment availability in Alpine catchment areas has at least doubled. Permafrost thawing and glacier retreat are accelerating Alpine mass movements and leading to increased landslides, rockfalls and large mudslides (Glade, Mergili, Sattler, 2019).

The driving force behind weather and precipitation patterns in mid-latitudes is the polar front and the associated jet stream. When this band of wind forms waves in a north-south direction, pronounced high- and low-pressure centers can develop, bringing intense heat on one side and heavy precipitation on the other. If these waves swing particularly far north and south, they can also come to a standstill and the weather conditions then remain stationary for a longer period of time. If the temperature difference between the polar region and the mid-latitudes decreases, the probability of strongly meandering jet streams and consequently the probability of stable, blocked low-pressure systems with prolonged heavy precipitation is much higher.

Causes of increased heavy rainfall include the higher water-holding capacity of a warmer atmosphere and changes in atmospheric circulation patterns, which may translate into future heavy rainfall increases in Austria. New research shows hourly heavy rainfall in Austria has increased by 15% over the last 40 years, very likely due to man-made climate change. The daily heavy rainfall changes are remarkably consistent with observed flood increases of about 8% in large catchments. The hourly heavy rainfall changes are similarly consistent with flood changes in small catchments, although the flood increase is stronger (25% over the last four decades) (Haslinger et al., 2025).

UNUSUAL EXTREME EVENTS AND DRIVING WEATHER PATTERNS - EXAMPLES FROM 2018 – 2025

In recent years, Austria has seen a significant increase in persistent weather patterns in the context of the climatic trends described above, which have led to extreme and repeated heavy precipitation and storms, triggering various extreme events such as flash floods, debris flow or mass-movements (depending on the region affected). The predominant weather pattern is a pronounced trough of low pressure establishing itself over Western Europe, the Iberian Peninsula or Italy, which pushed very warm air, some of it directly from North Africa, towards the Alpine region. This strong south-westerly upper air flow is regularly interspersed with a series of disturbances, which bring heavy rainfall especially to the southern side of the Alps, sometimes persistent over a period of several weeks. In some cases, the low-pressure systems move from the Mediterranean region across Austria towards Eastern Europe, creating a so-called "Vb-like" weather pattern that transported large amounts of moisture also into the northern side of the Alps (Stangl et al., 2020). Some key torrential events in Austria of the last decade are listed in Tab. 1.

Tab. 1 Major extreme torrential events 2018 – 2025 in Austria (examples)

Event Date	Description of Event
Oct 29 to Nov 1 2018	Heavy rain (up to 650 mm/3-days) and foehn storm (up to 200 km/h wind speed) in **Carinthia and East Tyrol**. The consequences were debris flows, flooding and extreme windthrow in protective forests, followed by the bark beetle disaster of 2022/23 in the protective forests
Nov 2019	More than 600 mm of snow- and rainfall in three weeks in **Carinthia, East Tyrol and Salzburg** north and south of Alpine Main Ridge (Lungau, Gastein Valley), triggering sudden snowmelt, flooding and extreme density for shallow landslides and slush flows
June 28 to 29 2022	Three consecutive precipitation events within 6 hours with a cumulative regional average precipitation intensity of 99 mm/h, with highest intensities (180 mm/h, 40 mm/15 min) causing severe flooding and debris flow events in **central Carinthia** (Gegendtal)
Aug 28 2023	An exceptional heavy-rainfall event affected the **Rauris Valley Salzburg** (approx. 130 mm of precipitation within around 15 hours) triggering an enormous debris flow event from Pilatuskar (Kolm Saigurn) with approx. 1 mio. m³ of unconsolidated paraglacial sediments after glacier retreat
Sept 12 to 16 2024	Persistent and extremely heavy rainfall in of **Lower Austria, Vienna and Upper Austria** received up to more than 400 mm of rain within five days, triggering severe flooding, landslides and mudflows. The event was one of the most extreme precipitation events recorded in Austria and made September 2024 the wettest September in Austria's measurement history

June 30 2025	In the **Gschnitz valley in Tyrol** a highly localized, convective storm cell produced extreme short-duration rainfall with more than 100 mm of precipitation falling within two hours. The resulting flash-flood conditions triggered multiple debris flows and landslides of unknown dimension.

EFFECTS ON EXISTING PROTECTION SYSTEMS, NEED FOR ACTION

Climate change is increasing the relevance of extreme hydrometeorological events for torrent control systems in Austria. More frequent and intense heavy-rainfall events can generate exceptionally high peak discharges, increased bedload transport, debris flows and woody debris, placing loads on protection structures that may exceed their original design assumptions. Climate change also directly affects the sediment regime of torrent catchments. Glacier retreat, permafrost degradation, slope instability, mass-movements and changes in vegetation can multiply the availability of loose sediment. Consequently, future events may not only involve more water, but also substantially greater sediment loads and more complex process combinations. The protective function of existing structures may therefore be challenged even where the hydraulic capacity itself remains sufficient.

New research shows, that while the indices of triggering precipitation and the number of exposed buildings increased steadily, frequency, magnitude and seasonality of damage-inducing torrential flooding did not show clear trends. This contradiction was attributed to a strong compensatory effect of the increasing number of technical mitigation structures in Austria (Schlögl et al., 2019). Hence, the maintenance of these structures is of paramount importance to counteract future effects of climate change on the magnitude and frequency of events and the increasing demand for land development in hazard-prone areas. Furthermore, it is essential to focus on the overall effectiveness of the protection systems and to give priority to key structures during safety assessments. In future, it will be necessary to increase the robustness of the protection systems and to incorporate redundancies that can tolerate even partial failure of protective structures due to extreme events, without collapse of the entire protective system, while accepting limited damages. Overall, climate change requires a shift from designing protection structures primarily for historical hazard conditions towards adaptive and process-based maintenance management for protective systems, including updated hazard scenarios, increased sediment retention capacity, robust structural design, improved monitoring and systematic supervision.

The three major key areas of action in the Austrian strategy for torrent control are:

- ✓ *Field of action 1: Resilient protection systems*

  In the ongoing condition monitoring of all 191,000 protective structures of the WLV, the functionality of the approx. 8,000 key structures in particular must be checked and evaluated. Existing protection systems must be adapted or expanded where necessary and their reliability increased.

- ✓ *Field of action 2: Effective sediment management*

  Existing concepts for the retention of bedload in the catchment area must be assessed and expanded if necessary. In addition, suitable, cost-effective recycling routes must be created for the management and removal of the resulting bedload and the necessary storage areas must be ensured. Establish long-term sediment monitoring in the catchment areas of the Hohe Tauern mountains.

- ✓ *Field of action 3: Integral risk reduction for mass movements*

  Intensive monitoring programs are necessary as a basis for assessing the risk of gravitational mass movements. Building on this, protection concepts are to be developed that reduce the risk efficiently and sustainably. The public awareness for the increasing risk of mass-movements in Alpine area has to be strengthened.

THE NEW AUSTRIAN APROACH OF PROTECTIVE SYSTEMS ENGINEERING

Torrent control in Austria has shifted the focus of maintenance from the single protection work and singular construction project to the entire protection system of a torrential catchment and a sustainable "cradle-to-cradle" management of these systems. Hence, an appropriate Protective Systems Engineering approach (PSE) has been developed.

According to the Austrian standard ON B4800 (2025) a protective system is defined a technically, functionally or spatially delimited set of interacting measures that serves the protective objective – usually the reduction of hazards and risks to an acceptable level. The complexity of multifunctional protective objectives and extreme events triggered by global warming require the further development and adaptation of protection concepts and associated engineering plans towards this 'system approach'.

The according requirements for the design of protective systems are:

- ✓ Alignment of protective systems with technical, economic and social requirements
- ✓ Ongoing optimization of existing protective systems based on monitoring, evaluation and documentation of system functions
- ✓ Ongoing quality assurance of the protective performance, including risk management for system failure and damages
- ✓ Increasing the resilience of protective systems by strengthen the robustness of structures and the redundancies within the systems
- ✓ Sustainability of protective systems by focusing on the entire life cycle ("cradle-to-cradle")

A major part of protective system engineering is the Technical Adaptation Management (TAM) and Protection System Integration (PSI): Protective systems are subject to constant adaptation due to changing environmental conditions (especially climate change), the effects and consequences of extreme events, technological developments and the necessary adaptation to the state of the art, as well as changed safety expectations (risk acceptance). TAM controls the planning, timely implementation and documentation of these adaptations to the protective system. PSI aims to reconfigure, expand and realign existing systems as part of a refurbishment campaign at the end of the first life cycle or after severe damage caused by extreme events. It also includes the integration of new components and safety features into existing protection systems.

An additional pillar of protective systems engineering is the Maintenance Management (MM): A prerequisite for the sustainable effectiveness of protective systems over their entire service life is the continuous inspection and condition assessment (including functional assessment) of the protective structures as well as the recording and analysis in a building database. The results of the condition assessment form the basis for the maintenance strategies, the timing and scope of maintenance and repair measures, the identification and implementation of improvements to the protective system, and the decision on how to handle the measure at the end of its service life (renewal, removal, controlled decay).

CONCLUSIONS AND COMPLEMENTARY STRATEGIC PROGRAMS

Global warming is scientifically proven to lead to an increase in the frequency and intensity of extreme natural disasters in the Alps and to a shift in their seasonality. Protective structures are currently able to compensate for this increase in risk to some extent. In the future, it will be necessary to further develop existing protective structures in line with the 'Protective Systems Engineering' approach, thereby adapting their resilience to the effects of global and climate change in the Alps.

The Austrian Federal Ministry has issued several strategies, that take into account these goals and principles and ensure that investment in protective measures meets the growing demands posed by climate and societal changes in the Alpine region:

- ✓ *Strategy die.wildbach 2030* (Corporate strategy of the Austrian Service for Torrent and Avlanche Control, since 2004, renewal cycle every 5 years)
- ✓ *Action Program GeoMonitorAT* (Monitoring and Risk Management for Big Mass movements in the Alps)
- ✓ *Action Program Climate/Safety/Living space* (Climate-adapted investment priorities in the field of protection against natural hazards)

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