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Impacts of Natural Hazards and Climate Change on EU Security and Defence

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Abbreviations

ALA	American Lifelines Alliance
CAL FIRE	California Department of Forestry and Fire Protection
CF SEDSS	European Defence Agency Consultation Forum for Sustainable Energy in the Defence and Security Sector
CSDP	European Union Common Security and Defence Policy
DOD	United States Department of Defense
DSCOVR	Deep Space Climate Observatory
EC	European Commission
EDA	European Defence Agency
EDSTAR	European Defence Standards Reference System
ENTSO-E	European Network of Transmission System Operators for Electricity
EPA	United States Environmental Protection Agency
EU	European Union
FEMA	United States Federal Emergency Management Agency
GHG	Greenhouse Gas
GIC	Geomagnetically Induced Current
ISO	International Organization for Standardization
JRC	European Commission's Joint Research Centre
MOD	Ministry of Defence
NASA	United States National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NATO SPS	North Atlantic Treaty Organization Science for Peace and Security Programme
NBS	Nature-Based Solutions
NOAA	United States National Oceanic and Atmospheric Administration
NRA	National Risk Assessment
POL	Petroleum/Oil/Lubricant
SERDP	United States Department of Defense Strategic Environmental Research and Development Programme
STANAG	North Atlantic Treaty Organization Standardization Agreement
UCPM	European Union Civil Protection Mechanism
UN	United Nations
UNDRR	United Nations Office for Disaster Risk Reduction
UNSC	United Nations Security Council
US	United States
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey

Executive Summary

Natural hazards and climate change can negatively affect military installations, military assets, supplies and operations and are a growing concern to *European Union* (EU) security and defence. In addition to direct impacts on installations, including community infrastructure and utilities used by the military (e.g., roads, bridges, energy, water), they can also affect military capability and mission execution, for example via increased demand for military support activities, both domestically and internationally, and through causing increased tensions, country instability and conflict escalation. The military may also incur higher running costs for maintenance, repair or replacement of infrastructure and equipment and face increased health and safety risks from natural hazards and climate change (e.g. more hot days).

Currently, only little information on natural hazard and climate change impacts on military infrastructure and operations in the EU exists or is publicly accessible. In support of the *EU Climate Change and Defence Roadmap* and capitalizing on data and studies available from non-EU countries, the *European Commission's Joint Research Centre* performed a study to:

1. Expand the understanding of the impacts of natural hazards and climate change on future EU security and defence;
2. Identify existing gaps and limitations in the path towards resilience to natural hazards and climate change of the military in Europe;
3. Recommend concrete actions to strengthen resilience, climate neutrality and environmental sustainability aspirations of the military, while safeguarding operational effectiveness.

The study clearly shows that neglecting natural hazards and climate change in the context of EU security and defence can have major consequences, with implications that may extend beyond the military.

EU security and defence in a changing climate

Europe already faces a number of defence and security threats which will be exacerbated by natural hazards and climate change. They will also modify the conditions in which the military operate, adding uncertainty, adversity and complexity. Given the current rate of global warming, the south of Europe is bound to face an increase in heatwave, drought, and wildfire hazards. Rainfall floods may increase in frequency, especially towards Scandinavia and eastern Europe during winter, central and north western Europe may experience an increase in river flood discharges, and the northern coast of Europe may face a higher coastal flood hazard. Furthermore, permafrost regions in the Artic and the Alps will likely thaw. In addition to these, other climate-related hazards for which evidence for trends is still lacking (e.g., storms, lightning and landslides), geophysical hazards, space weather, compound events and cascading effects need to be considered.

The geopolitical landscape is already changing in parts of the world due to climate change. The melting artic, for example, may create new disputes for sea routes, territories and resources and make way for new power projections. Further degradation of living conditions in some regions of the world, for example the Sahel and the Horn of Africa, at least partially associated to natural hazards and climate change, may potentiate migration and conflict. Natural hazards and climate change can also open new opportunities for hybrid attacks.

In addition to creating new threat scenarios for which the military should prepare, natural hazards and climate change can also directly disrupt military installations, the critical infrastructure they depend on, and operations. For example, heat stress may increase the number of no-training and no-testing days. Flooded facilities may result in the shutdown of airstrips. Hurricanes may force evacuation and unplanned sorties. Power outages may impair command and control. Water shortages may lead to disputes with surrounding communities. Sand storms may jam or damage weapons systems. Space weather may disrupt communications. The degradation of military land may force the relocation of activities. Natural hazards and climate change may ultimately affect the structure and composition of the military through, for example, "base realignment and closure".

Is the EU military prepared for climate change?

The study showed multiple existing gaps related to policy, knowledge, methods and tools, as well as practices that should be addressed to better prepare for the likely direct and indirect consequences of a warming climate. For example:

- The negative impacts of natural hazards and climate change are indirectly addressed by current policies, e.g. related to disaster risk management, chemical or nuclear accident prevention, or

climate change adaptation. However, there is no tangible scope or mandate for their application in this context.

- There is a lack of dedicated programs at EU level tasked with research, development and innovation (e.g., similar to the NATO Science for Peace and Security Programme or the US Environmental Research and Development Program).
- There is a lack of (open) data on the direct and indirect impacts of natural hazards and climate change on the EU military and on defence critical infrastructure, as well as on their exposure and vulnerability.
- There is only incomplete knowledge about the security implications of natural hazards and climate change (e.g., conflict forecast, threat- and burden multiplication).
- Risk reduction and resilience may entail trade-offs in terms of climate neutrality and environmental sustainability, something that is not well understood.
- Risk assessments tend to focus on individual hazards, structures and regions rather than using a systems approach. They also often fail to address future changes in climate-related natural hazards.
- There is a delay in the adoption of adaptive planning (e.g. contingency and business continuity) and management specific to each military installations and defence critical infrastructure.
- There is a lack of stress tests (e.g., power outage) and crisis gaming (including scenario analysis and table top exercises) with a focus on natural hazards and climate change. This would be essential for decision making in the face of uncertainty and complexity of future threats to the military.
- There is a lack of tools that can handle the complexity of system-wide risk assessments. Similarly, there is a scarcity of tools to analyse trade-offs between the implementation of risk reduction and resilience measures, climate neutrality, environmental sustainability, operational effectiveness and cost.
- There may not be enough integration, in military planning and investment cycles, of risk assessment that accounts for all hazards, including compound and cascading events.
- There is a need to strengthen collaboration and effective coordination across military departments and jurisdictions (e.g., cross-border).

Strengthening resilience and ensuring business continuity

Closing the aforementioned gaps and building resilience of the military to natural hazards and climate change requires the implementation of actions and measures that can be local, national or regional. The study discusses possible structural, non-structural and nature-based solutions per natural hazard at a local scale. Additionally, we propose short-, medium- and long-term measures at European scale with a view to help EU defence stakeholders to pick up momentum in their path towards resilience, carbon neutrality and environmental sustainability. The following non-exhaustive list of proposed actions complements the actions identified in the *EU Climate Change and Defence Roadmap*:

Short-term:

- Define EU defence critical infrastructure based on mission assurance.
- Develop a pilot study to understand current risk management practice.
- Further investigate the impacts of natural hazards and climate change on defence critical infrastructure and on EU security. An example is the ongoing EDA-JRC joint study focusing on defence-related critical energy infrastructure in the context of the Consultation Forum for Sustainable Energy in the Defence and Security Sector (CF SEDSS);
- Develop scenarios for crisis gaming, especially considering high uncertainty cases.
- Define a long-term strategy to support risk reduction and resilience building of military installations and defence critical infrastructure in the EU.

- Engage EU defence in resilience, carbon neutrality and environmental sustainability.

Medium-term:

- Establish a permanent program to advance research, development and innovation to support the MODs.
- Report on the threats of natural hazards and climate change to EU security and defence.
- Develop dedicated guidelines and standards for EU defence (e.g., similar to the *US Department of Defence Unified Facilities Criteria*).
- Define resilience, carbon neutrality and environmental sustainability goals for EU defence.
- Define acceptable risk and risk profiles for EU defence.
- Prioritize resilience measures with a focus on mission assurance, cost effectiveness and feasibility.
- Integrate natural hazard and climate change in conflict forecasts.

Long-term:

- Reduce the environmental footprint of EU defence (e.g., circular economy, green procurement) which has the additional advantage of reducing resource dependency, increasing resource efficiency, minimizing waste and producing savings.
- Transition to low carbon activities (e.g., renewable energy, vehicle-to-grid, biofuel, hydrogen) whenever it does not compromise operational effectiveness.

The implementation of measures may necessarily entail trade-offs, e.g., the loss of process efficiency (e.g., recharging time and autonomy of electric vehicles), but also a significant initial investment, even if they can produce cost savings in the long run (e.g., renovating buildings to improve energy efficiency). Special care needs to be given to safeguard operational effectiveness and military capability, as a 'greener' military that is unable to fulfil its mission does not serve any purpose.

Measure implementation should also not precede risk assessment, as they need to be looked at, objectively, from an angle of cost-effectiveness, feasibility, unintended consequences (e.g., backwater effect in floods) and added benefits/opportunities (e.g., ecosystem restoration and increase in carbon sequestration). On the other hand, some measures that may be considered optimal to reduce damage from a specific natural hazard may actually aggravate other effects, for example buried pipelines may perform better in the case of an earthquake, but may be more prone to erosion in the case of a flood.

A vast entity like the military needs time to adapt which requires picking up momentum as fast as possible. Delayed action may increase the risk of failure, both in terms of infrastructure and military capability, and the potential for greater losses.

1 Introduction

Natural hazards and climate change can negatively impact military (fixed) installations, military assets, supplies and operations and are of concern to EU security and defence. Past examples highlight the damaging potential of natural hazards in the military sector, for example in October 2018 Hurricane Michael damaged almost every structure belonging to *Tyndall Air Force Base* in the *United States* (US), and six months later large parts of Offutt Air Force Base were flooded. According to the press ([1]), the overall reconstruction cost for both military installations was estimated at US$4.9 billion.

Countries such as France, Germany and the US, to name a few examples, have started to take the implications of climate change and natural hazards for security and defence seriously and have released some important publications in this respect (e.g., BMU, 2002; DOD, 2019a; IRIS, 2014). At the same time, this has been a relevant topic for international organizations such as the *North Atlantic Treaty Organization* (NATO) and the *United Nations* (UN) (e.g., UNSG, 2009; NATO, 2010). **Currently, only little information on natural hazard impacts on military infrastructure and operations in the EU exists or is accessible. However, initiatives to understand the implications of climate change for military capability have already been launched in Europe.**

1.1 Goals

The main goals of this study, in line with the *EU Climate Change and Defence Roadmap* (EEAS, 2020), the *European Strategic Compass* ([2]) and the *European Green Deal* (EC, 2019a), are to:

4. Expand the understanding, and inform the ongoing work (e.g., Meyer et al., 2021), of the impacts of natural hazards and climate change on EU security and defence;
5. Identify existing gaps and limitations in the path towards resilience to natural hazards and climate change of the military in Europe;
6. Recommend concrete actions to strengthen resilience, climate neutrality and environmental sustainability aspirations of the military, while safeguarding operational effectiveness.

1.2 Methodology and assumptions

To produce this study, the authors have made use of the substantial knowledge existing in the *European Commission's* (EC) *Joint Research Centre* (JRC), in particular the extensive work produced, and experience accumulated, by the Techrisk sector over the years. The authors have made use of official documents, reports, scientific publications and images that were publicly available. In some cases, non-conventional materials such as newspapers, multimedia (e.g., videos) and maps were consulted, with due caution, to confirm findings, provide intuition and context.

It is important to note that no analysis of official data from the *EU Ministries of Defence* (MOD) or the military in Europe was performed, as it was not accessible at the time of writing. The authors tried to capitalize on whatever information was publicly available from non-EU countries (e.g., the US) in order to extrapolate to the European case.

This study is structured in the following way: in Chapter 2 an overview of the different natural hazards and climate change at the global and European scale, and on how they can impact technological systems is presented; in Chapter 3, the threats that natural hazards and climate change pose to EU security are explored; in Chapter 4, the composition of military installations, the backbone of military capability, how natural hazards and climate change may increase the potential for disruption, loss or damage, and their exposure is explored; in Chapters 5 and 6, negative impacts are exemplified through historical case studies, grouped into climate-related, geophysical and space-weather events; and in Chapter 7, an analysis of gaps and barriers is presented followed by recommendations on how to close these gaps.

(1) Doubek, J. (2019). Air Force needs almost $5 billion to recover bases from hurricane, flood damage. National Public Radio (accessed 1 July 2021). https://www.npr.org/2019/03/28/707506544/air-force-needs-almost-5-billion-to-recover-bases-from-hurricane-flood-damage?t=1619018052827&t=1620148880570

(2) European External Action Service (2021). Towards a Strategic Compass (accessed 1 July 2021). https://eeas.europa.eu/sites/default/files/towards_a_strategic_compass.pdf

2 An overview of natural hazards and climate change

The *United Nations Office for Disaster Risk Reduction* (UNDRR, 2009), defines a natural hazard as a "Natural process or phenomenon that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption or environmental damage".

The occurrence of a natural hazard in a particular location is just one of a number of conditions for disaster. Communities infrastructure and assets may or may not be present within the impact area, may or may not be vulnerable to the impacts, and may or may not be able to cope, adapt and quickly recover (EC, 2012; *European Commission High Representative of the Union for Foreign Affairs and Security Policy*, 2017).

Natural hazards are often grouped according to a particular scientific subject, for example earthquakes, volcano eruptions and tsunamis are often classified as geophysical hazards (Bokwa, 2013). In this study, natural hazards are grouped according to their relation to climate. In other words, if climate change (i.e., "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods", Article 1 of the *UN Framework Convention on Climate Change* (UNFCCC, 1992) modifies the characteristics (i.e., duration, extent, frequency, intensity, location, seasonality) of a natural hazard then it is classified as a climate-related natural hazard. Figure 1 summarizes some of the existing scientific evidence (less towards the left) for a relation between the changing characteristics of a natural hazard and climate change.

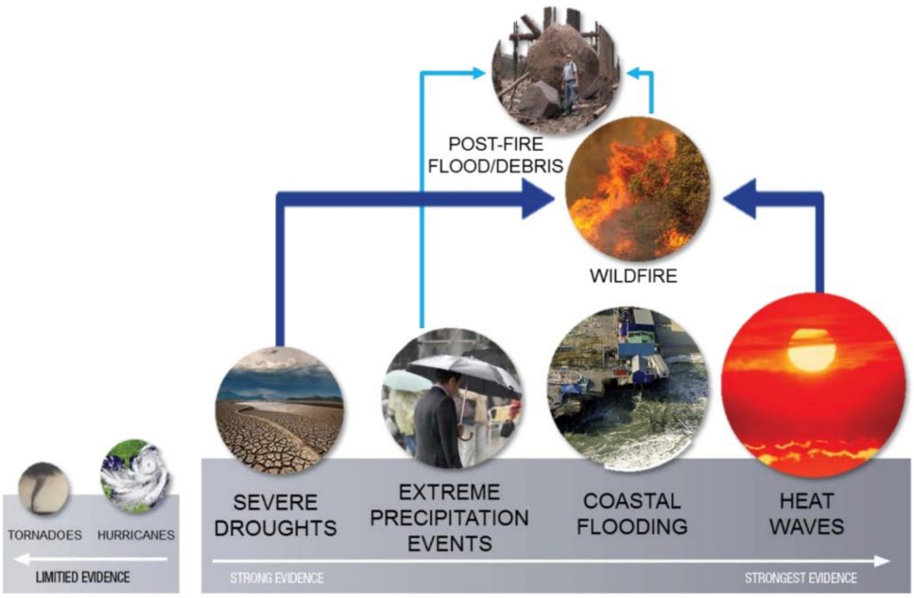

Figure 1. Supporting evidence for changes in natural hazards due to climate change (NAVFAC, 2017). Source: Kate White/USACE.

Box 1. A note on climate change and climate scenarios.

Climate change is unambiguously associated to the concept of climate scenarios: quantitative descriptions of the global and regional climate, global warming projections of greenhouse gas (GHG) emissions from human activities (anthropogenic) and their concentration in the atmosphere.

Although disaster fatalities in the world are mostly due to geophysical hazards, **climate-related disasters have dominated the number of occurrences and economic losses from 1998 to 2017** (UNDRR/CRED, 2018). Moreover, some climate-related natural hazards are becoming more intense and more frequent with global warming (UNDRR, 2019; WEF, 2021) driving higher disaster risk associated to extreme weather, floods, landslides, drought and wildfires (UNDRR, 2019; Gencer et al., 2018). In 2020, for the first time, climate change ranked highest in terms of concern and in 2021 it only lost its position to infectious diseases, due to the ongoing COVID-19 pandemic (WEF, 2021). Irrespective of an effective reduction of GHG emissions, some of the impacts of climate change are already unavoidable (Feyen et al., 2020), for example sea level rise will continue well beyond the end of the century (UNDRR, 2019; IPCC, 2018).

In Europe, disasters are on the rise and have overwhelmed national response capabilities several times. Between 1980 and 2017, the combined losses of climate-related and geophysical natural hazards exceeded €500 billion, with ca. 70% caused by high-impact low-probability events that make ca. 3% of all events (EC, 2020a) ([3]). Some of these events can be attributed to the changing of the climate, but also the changing of exposure and vulnerability of communities and infrastructure (EC, 2020a).

Considering only assistance requests at the European Union level (Figure 2), and acknowledging that the inclusion of all individual national responses could change this picture, **wildfires represent the most common natural hazard in Europe, while heatwaves are the deadliest, and storms, floods (largest share) and earthquakes the costliest** (Annunziato et al., 2013; EC, 2020a).

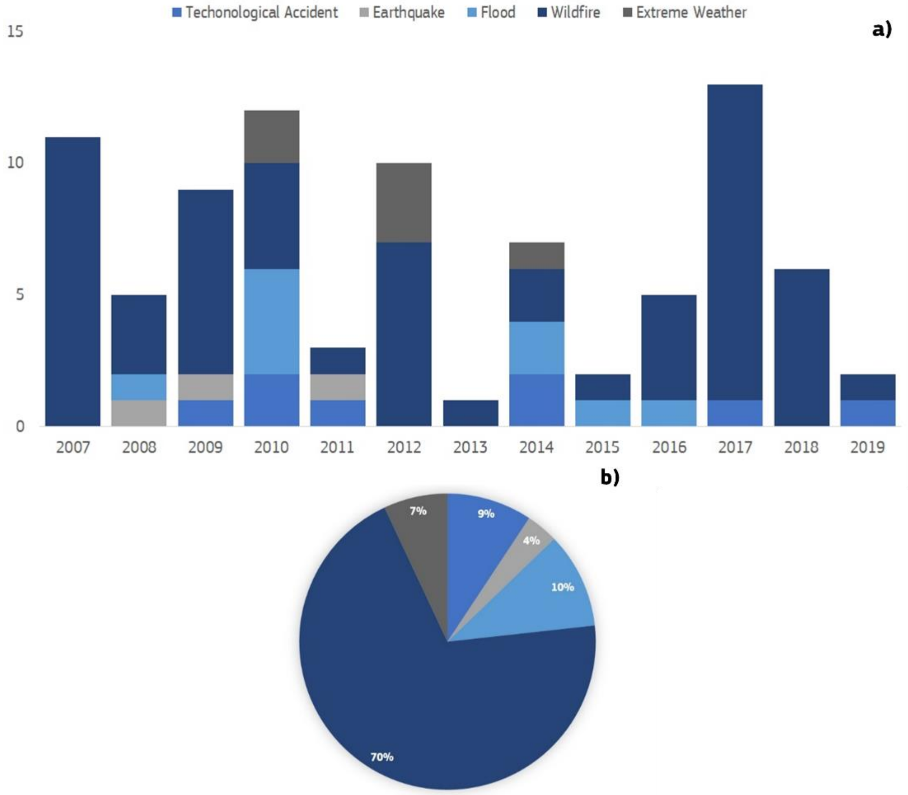

Figure 2. Assistance requests to the *European Union Civil Protection Mechanism* (UCPM) per type of event from 2007 to 2019; a) Number of requests per year; b) Share of requests for the whole period (based on EC, 2020a). Extreme weather refers to a combination of extreme temperatures, storms and heavy precipitation. Note that individual national response activities are not included.

In general terms, an increase in extreme heat is expected in Europe. Water scarcity, drought, ecosystem stress, with loss of ecosystem services, and wildfires are expected to hit southern Europe the most., while an increase in rainfall and floods, and a reduction in ice cover and permafrost is expected particularly in northern Europe (EEA, 2020; EC, 2020a; Feyen et al., 2020).

Box 2. A note on the assistance requests to the *European Union Civil Protection Mechanism* (UCPM).

The number of assistance requests to the UCPM assistance do not include individual national civil protection and military assistance requests.

([3]) European Environment Agency. Economic losses from climate-related extremes in Europe (accessed 1 July 2021). https://www.eea.europa.eu/data-and-maps/indicators/direct-losses-from-weather-disasters-4/assessment

2.1.1 Climate-related natural hazards

2.1.1.1 High temperature

Global average surface temperature is today ca. 1 °C above pre-industrial levels and the last few years are the warmest on record ([4]). At the current rate, we are on track for a 3 °C increase by the end of the century (WEF, 2021). In Europe, warming has been greater than the global average, and from 2009 to 2018 the mean annual temperature overland was between 1.6°C and 1.7°C (EC, 2020a). **Further warming may lead to an increase in length, intensity, and frequency of heatwaves in all land regions** (i.e., several days of excessively high temperatures), heat-related mortality (EC, 2020a; EEA, 2020; Feyen et al., 2020; IPCC, 2018; Toreti et al., 2019), and major pollution accidents (ARIA, 2012b). **In Europe, extreme hot days are expected to increase** (IPCC, 2018). For the military this means more challenging operating conditions for personnel and equipment, but also military installations in general. Heatwaves may lead to drought, water shortage, higher energy demand for cooling, power outages, decline in ice cover and permafrost, and decline in air quality (EC, 2020a; UNDRR, 2019; Gencer et al., 2018).

2.1.1.2 Low temperature

While cold extremes are expected to decrease in intensity, frequency and duration in a warming climate (IPCC, 2013, 2018), phenomena related to **cold weather will continue to remain a threat to critical infrastructure and to sectors relying on them at least until mid-century** (Bailey et al., 2021; EC, 2020a) ([5]). Freezing of equipment, ice formation and physical loads due to accumulated and falling ice and snow have been a frequent source of accidents involving the release of hazardous materials or power blackouts (ARIA, 2012a; Krausmann et al., 2017) ([6]). Nevertheless, low temperature remains an underestimated threat.

2.1.1.3 Floods

A global scale intensification of the water cycle is expected with global warming and with it also heavy precipitation (Donat et al., 2016; Gencer et al., 2018; IPCC, 2013, 2018). In Europe heavy precipitation is expected to increase, a trend that is clearer especially towards the north (EC, 2020a; Feyen et al., 2020; IPCC, 2021; Toreti et al., 2013). On the other hand, sea level rise, due to ocean thermal expansion and ice loss driven by global warming and GHG emissions, will likely reach half meter or more by the end of the century, is already unavoidable and will continue beyond 2100 (DeConto et al., 2021; IPCC, 2018; Kopp et al., 2014).

Floods can be of slow or rapid onset (flash floods) and are essentially of three types: coastal, river and rainfall. Costal floods are caused by the combination and interaction (e.g., Idier et al., 2019) between high tides, storm surge (i.e., temporary sea level rise due to changing atmospheric pressure and winds due to storms), waves, sea level rise, river flows in estuaries and coastal subsidence (i.e., lowering of ground due to groundwater loss outpacing recharge; for example in the Netherlands and in the Po River valley in Italy; Herrera-García et al., 2021). River floods occur when water level surpasses the height of river banks and water overflows to neighbouring land. High water levels are a result of excessive runoff from rainfall or snowmelt, changes in river morphology, blocking of river channels (e.g., ice jam, log jam), coincidence of discharge peaks at river confluence or coincidence with high tides at tidal influenced stretches. Rainfall-induced flash flooding occurs because excessive rainfall surpasses soil infiltration capacity or soil is excessively saturated (high soil moisture or thick snow cover), or even because it surpasses urban drainage capacity. Flooding can also result from the failure or overtopping of a dam or flood defence. From 1998 to 2017, floods were the most common disaster at the global scale and affected the highest number of people (UNDRR/CRED, 2018). In Europe, floods have been one of the most frequent and damaging disasters (EC, 2020a). In general terms, **under all climate scenarios, the frequency and magnitude of floods may increase due to changing rainfall and runoff, and sea level rise in the case of coastal floods** (Alfieri et al., 2015a, 2017; Gencer et al., 2018; IPCC, 2018; Pall et al., 2011; Vousdoukas et al., 2017, 2018). **In Europe, without measures to reduce risk and increase resilience, major economic losses are expected by the end of the century** (Alfireri et al., 2015b; EC, 2020a; Feyen et al., 2020). Rainfall floods

([4]) Copernicus Climate Change Service (C3S). Copernicus: 2020 warmest year on record for Europe; globally, 2020 ties with 2016 for warmest year recorded (accessed 1 July 2021). https://climate.copernicus.eu/2020-warmest-year-record-europe-globally-2020-ties-2016-warmest-year-recorded

([5]) Morris, S., Weaver M. and Khomami, N. (2018). Beast from the East meets storm Emma, causing UK's worst weather in years. The Guardian (accessed 1 July 2021). https://www.theguardian.com/uk-news/2018/mar/01/beast-from-east-storm-emma-uk-worst-weather-years

([6]) CBC News (2013). Toronto ice storm leaves 230,000 without power (accessed 11 August 2021). https://www.cbc.ca/news/canada/toronto/toronto-ice-storm-leaves-230-000-without-power-1.2473543 will likely occur more frequently throughout Europe, but more during winter and towards Scandinavia and eastern Europe (EC, 2020a). Increasing trends in river flood discharges are observed in most of central and north western Europe (e.g., Bertola et al., 2020, 2021; Blöschl et al., 2019). In particular, severe river floods with a present-day return period of 500 years are expected to become more frequent in some European river basins such as the Po in Italy, the Duero in Spain and Portugal, the Garonne in Spain and France, the Ebro in Spain, the Loire and Rhone in France, and the Rhine in Germany and the Netherlands (EC, 2020a). On the other hand, the northern coast of Europe may face higher coastal flood hazard (e.g., Vousdoukas et al., 2017), and damage from coastal floods is expected to rise in all *EU Member States* with a coastline, especially Germany, Denmark, France, Italy and the Netherlands (EC, 2020a).

2.1.1.4 Drought

Drought is a prolonged deficit of rainfall, soil moisture and/or surface and groundwater in a given region compared to each respective long-term average. Drought is exacerbated by high temperatures (heatwaves), low relative humidity, intense water use and poor water management (Naumann et al., 2021). It is a slow-onset event with widespread, mostly indirect, impacts on well-being, ecosystems, food, water and energy security (EC, 2020a; Gencer et al., 2018; Naumann et al., 2021; UNDRR/CRED, 2018; UNDRR, 2019). Drought can for example cause water shortages, reduce soil moisture, produce cracked soil, damage infrastructure, and dry out vegetation, create favourable conditions for severe wildfires, lead to land degradation (e.g., desertification – land unable to support plant growth), erosion, increase in sediment loads, siltation and water contamination. Droughts are second only to floods in terms of the number of people affected worldwide, however, they only represent 4% of total economic losses, even if substantial in a few countries (UNDRR/CRED, 2018). **Due to global warming and changing socio-economic conditions, droughts are expected to last longer, become more frequent and more severe in several regions of the world** even with a reduction of GHG emission (Naumann et al., 2021; UNDRR, 2019; Ward et al., 2020). Since 1951, Europe has seen an increase in droughts and associated economic losses (Annunziato et al., 2013; EC, 2020a; IPCC, 2018; Ionita et al., 2021; Naumann et al., 2021). **The Mediterranean region, and in particular the Iberian Peninsula, could see a significant rise in drought conditions and a decline in water availability** with consequences for hydro- and thermal power generation, including the forced shutdown of power stations (EC, 2020a; Feyen et al., 2020).

2.1.1.5 Storms

Windstorms, including cyclones and convective storms, are a weather phenomenon characterized by gusts and strong sustained winds that may be accompanied by precipitation (e.g., hail), lightning, suspended particulate matter (e.g., dust), waves and storm surge – the former two only if large water bodies are involved. A cyclone is a large-scale rotating storm with low atmospheric pressure in its centre that forms along the boundaries separating air masses of different temperatures (extratropical cyclone) or over warm waters (tropical cyclone), while convective storms are severe, relatively short-lived, localized storms that form due to convection (Poljanšek et al., 2018). Globally, between 1998 and 2017, windstorms were the costliest disaster and ranked second in terms of occurrence and in fatalities (CRED/UNDRR, 2018). In Europe, for the same period, windstorm damage amounted to €163 billion (EC, 2020a) and has increased over the last decades (Spinoni et al., 2019), with coastal areas and outermost regions particularly affected (EC, 2020a). Although windstorms are grouped as a climate-related hazard, **it remains unclear if global warming will produce any significant trend in windstorms** (EEA, 2017; EC, 2020a; IPCC, 2013, 2018; Poljanšek et al., 2018).

The occurrence of lightning can often be associated to tropical cyclones and convective storms. However, they can also be triggered by volcanic plumes (Schultz et al., 2020) or even aircrafts (Pavan et al., 2019; Wilkinson et al., 2012) and potentially ships ([7]). Between one and two billion lightning strikes/year are estimated to occur globally (Mackerras et al., 1998; Poljanšek et al., 2018), while over Europe the number falls to between 0.4 and four lighting strikes per year per km^2 (Anderson and Klugmann, 2014; Poljanšek et al., 2018). Lightning is responsible for several thousands of deaths each year worldwide (Holle, 2016a, b). Although lightning is grouped as a climate-related hazard, **the increase in lightning due to climate change remains unclear**, which follows the same low confidence level as windstorms (e.g., IPCC, 2013; Romps et al., 2014). However, data from 2010 to 2020 show that the number of lightning strikes in the Arctic is increasing

([7]) Perkins, S. (2017). Cargo ships may be creating lightning at sea. Science (accessed 1 July 2021). https://www.sciencemag.org/news/2017/09/cargo-ships-may-be-creating-lightning-sea and correlates to the deviation of the yearly average temperature from the average for the period of 1951 to 1980 (Holzworth et al., 2021).

2.1.1.6 Wildfires

Although globally wildfires take a small share of all disaster occurrences, fatalities and economic losses (UNDRR/CRED, 2018), they have been the disaster that prompted the most requests for assistance in Europe (Figure 2). **The majority of European wildfires tend to occur towards the South** where fire weather (i.e., the conditions on which wildfires depend, such as high temperature, low humidity, low rainfall and strong wind), earlier and longer fire seasons, dried out vegetation, and the dominance of fire-prone species facilitate ignition and propagation (EC, 2020a; Feyen et al., 2020). Fire weather also determines the degree to which wildfires can be effectively managed posing numerous challenges to those responsible (DOD, 2014). The large majority of wildfire ignitions in Europe are man-made (by accident, such as toppled above-ground power lines, or intentional such as arson; Balch et al., 2017; Ganteaume et al., 2013), but lightning can also be a trigger (e.g., Moris et al., 2020). Wildfire frequency and intensity has been on the rise in Europe and in 2017 and 2018, they resulted in numerous fatalities and ca. €13 billion economic losses (EC, 2020a). **With climate change wildfires risk is expected to increase globally** (Brown et al., 2021; EC, 2020a; Feyen et al., 2020; IPCC, 2018; Jones et al., 2020; Smith et al., 2020; van Oldenborgh et al., 2021).

2.1.1.7 Rainfall-induced landslides

Landslides are the movement of rock and soil downslope due to strain and progressive failure often induced by rainfall or seismic activity (UNDRR, 2019). Despite landslides suffering from underreporting, they rank fifth in the number of disasters between 1998 and 2017 (CRED/UNDRR, 2018). Given that wildfires burn the vegetation that stabilizes hillslopes, and that wildfires, rainfall and thawing permafrost may increase with climate change, **it seems plausible that there will be more favourable conditions for landslides to occur in the future, however this is a subject that remains unclear** ([8]). In this study, landslides are grouped in climate-related natural hazards for the reasons listed before and exclude those exclusively triggered by seismic activity.

2.1.1.8 Permafrost thawing

Permafrost is ground that remains at or below 0 °C for two or more consecutive years. It differs in temperature (to ca. -13 °C), thickness (from less than 1 m to 1500 m), extent, depth of thawing, and mechanical strength (Anisimov and Reneva, 2006). Nelson et al. (2002) categorize it into: Continuous, underlying all surfaces; Discontinuous, influenced by factors such as climate, vegetation, presence of water, snow cover and thermal proprieties of the soil (Anisimov and Reneva, 2006; Suter et al.; 2019); or Sporadic, only in very specific circumstances such as peat deposits. **About a quarter of the Northern Hemisphere's land surface**, **including Artic Europe and the Alps, are permafrost regions** (Gruber, 2012; USARC, 2003), **which will likely thaw with global warming** (Hjort et al., 2018; IPCC, 2018). Biskaborne et al. (2019) found that, between 2007 and 2016, permafrost temperature increased on average 0.29 °C. The thickening of the active layer with warming, may not be of great concern for coarse soils, except perhaps during earthquakes (Edlund et al., 2019, Hubler et al., 2017), however, for ice-rich fine-grained sediments, its thawing results in non-uniform differential settlement (thaw subsidence) of the terrain, typically known as thermokarst terrain (Nelson et al., 2002; Suter et al, 2019), which can lead to structural damage and failure and degradation of military land, including training and testing grounds. . It should be noted that thawing permafrost releases methane, a powerful GHG, which may accelerate anthropogenic global warming (Froitzheim et al., 2021).

2.1.2 Geophysical hazards

2.1.2.1 Earthquakes

An earthquake is the shaking of the ground mostly due to the movement of the Earth's crust, which can lead to structural damage and failure. Furthermore, earthquakes can trigger landslides, soil liquefaction and tsunamis (EC, 2020a). In the last two decades, earthquakes resulted in more fatalities than any other natural hazard worldwide, they ranked third in terms of occurrences, and fourth in terms of people affected

([8]) Palmer, J. (2020). A Slippery Slope: Could Climate Change Lead to More Landslides? Eos: Science News by the American Geophysical Union (accessed 1 July 2021). https://eos.org/features/a-slippery-slope-could-climate-change-lead-to-more-landslides

(UNDRR/CRED, 2018). Earthquakes correspond to ca. 20% of all disaster-related economic losses that on average occur each year worldwide, however, in 2010 and 2011 the share reached ca. 60% (UNDRR, 2019). **In southern Europe the convergence between the Eurasian-African plates is responsible for a number of earthquakes, but smaller plates can also trigger earthquakes (e.g., Romania).**

2.1.2.2 Volcanoes

A volcanic eruption is a rupture of the Earth's crust with a release of lava, ash and other airborne material, and gases, which can also produce earthquakes, landslides, tsunamis and lightning. Volcanoes are most commonly located near the boundary of tectonic plates. Globally, there are ca. 1500 potentially active terrestrial volcanoes (Poljanšek et al., 2018), while **in Europe there are over 60 active volcanos, especially towards the south of Europe and outermost regions** ([9]), some with nearby communities.

2.1.2.3 Tsunami

A tsunami is a long period wave caused by a sudden displacement of a large water mass. It is often caused by an earthquake with epicentre near the coast or underwater, a coastal or submarine landslide, glacial calving or volcanic activity (Annunziato et al., 2013; UNDRR, 2019). A tsunami wave will increase in height as waters become shallower near the coast, and when superposed on sea level rise, tides and storm surge it may potentially lead to significant coastal flooding. **In Europe, the Mediterranean coast is at higher tsunami risk due to higher seismic activity and the presence of active volcanoes** (EC, 2020a).

2.1.3 Space weather

Space weather denotes the changing conditions in the space environment within the solar system, caused by disturbances in the Sun. These disturbances take the form of solar flares and coronal mass ejections that are distinguishable from the normal ejections of plasma from the Sun, the solar wind. These events occur frequently and most of the time have limited negative impacts, however, in specific conditions they can produce **geomagnetic and solar radiation storms**, which **may have multiple simultaneous and widespread negative impacts on infrastructure across different countries** (including those used by the military) (Krausmann et al., 2016), but also on satellites in orbit. The largest geomagnetic storm ever recorded was that of September 1859, known as the Carrington Event. According to Riley (2012), an event such as the Carrington Event has ca. 12% probability to hit Earth within the decade.

Space weather storms can disrupt global navigation satellite systems, disable or damage satellite's electronic components (e.g., sensors, solar panels), damage satellite data or cause its loss, disrupt satellite communications, affect satellite orientation and tracking, create satellite drag and orbital decay, generate higher radiation exposure at high altitudes (aviation) and in space missions, disrupt radio communications and generate radio blackouts in the Polar Regions (known as a polar cap absorption event), as well as disrupt radars and magnetic signature detection systems.

Furthermore, during a geomagnetic storm electric currents in the magnetosphere and ionosphere increase, which generates geomagnetically induced currents (GICs) on the surface of the Earth that enter any electrical conductor networks (e.g., power grids, non-fibre optic lines, pipelines, railways) through the ground (Piccinelli and Krausmann, 2015). Depending on the magnitude, frequency, geomagnetic latitude, ocean proximity, size and configuration of lifelines, and design of equipment (NERC, 2012), GICs can cause immediate or cumulative damages governed by the size, properties and topology of the electrical conductor network.

GICs can affect the power grid, particularly high-voltage low-resistance electric equipment, by creating voltage fluctuations, voltage control and protective relay problems, damage to transformers, heating, inefficient transmission, line tripping and outages, and the triggering of false alarms (Erinmez et al, 2002). GICs can also increase corrosion of buried pipelines, due to changing electro-chemical properties of the ground, rendering ineffective any cathodic protection, with consequent reduced service life and increased costs (Gummow, 2002). GICs can also affect railroad tracks, lead to transformer, signalling and station lighting failures, and train shutdowns (Krausmann et al., 2015, 2016a). Military installations and operation, can be affected indirectly, for example through disruption of electrical power supply, or the degradation of instrument landing systems' performance.

(9) European Catalogue of Volcanoes (accessed 1 July 2021). https://volcanos.eurovolc.eu/

Since particles are deviated towards the poles, northern latitudes in the EU are expected to be more exposed to space weather (Piccinelli and Krausmann, 2015).

2.1.4 Compound events

Often, negative Impacts are the result of compound events instead of individual natural hazards (IPCC, 2012, 2018). A compound event is a combination of two or more natural hazards or physical processes, occurring simultaneously or successively, possibly interacting (IPCC, 2012; Ridder et al, 2020; UNDRR, 2019; Zscheischler et al., 2018, 2020). The contributing natural hazards or physical processes can be of similar type or not, and may or may not be correlated (IPCC, 2012). For example, simultaneous peak discharges at a river confluence may cause or aggravate a flood. Rain over snow may lead to an increase in snowmelt and soil saturation, and result in flooding. Coastal flooding may occur due to a combination of coastal subsidence, sea level rise, high tide, storm surge and waves (Idier et al., 2019; Raymond et al., 2020). Rain after a wildfire may lead to flooding due to loss of vegetation and soil infiltration capacity, but also to erosion and landslides. A tsunamigenic earthquake, such as the 1755 Lisbon earthquake and tsunami (Tavares da Costa and Annunziato, 2014), can have more negative impacts than its individual components separately.

In Europe, two dozen of river floods and storm surge events have occurred simultaneously between 1870 and 2016 (EC, 2020a; Paprotny et al., 2017, 2018), and the western coast of Europe is found to be a hotspot for heavy rainfall and strong wind (Ridder et al., 2020). Furthermore, **the characteristics of compound events may be affected by climate change**, putting some regions (EC, 2020a; IPCC, 2018; Khanam et al., 2021; Naumann et al., 2021; Zscheischler et al., 2020) and critical infrastructure such as power grids (e.g., Khanam et al., 2021) at higher risk of damage and disruption.

Box 3. A note on the examples of compound events.

Although emphasis is given to flooding, one could easily think of different types of compounding natural hazards or physical processes, such as drought that often does not happen in isolation (IPCC, 2018; Naumann et al., 2021), or hot and dry weather and strong wind that create favourable conditions for wildfires to propagate.

2.1.5 Cascading effects

Most disasters involve cascading effects (Pescaroli and Nones, 2016). A cascading effect is the propagation of negative impacts in a system (e.g. power grid), system of systems (e.g., defence), or even broadly on society. Cascading effects are characterized by the existence of vulnerabilities and dependencies and the occurrence of a primary negative impact (the initiating event, also known as trigger) on one or multiple components of a system (EC, 2020a; UNDRR, 2019; Pescaroli and Nones, 2016). For example, a tsunamigenic earthquake may trigger the release of toxic material at a coastal chemical facility and floodwaters may disperse it over a wide area, creating an important secondary hazard to the population (Hokugo, 2013; Hokugo et al., 2011).

When the trigger of a technological accident (e.g., fire, explosion, toxic release) is a natural hazard, a physical process, or any combination thereof (i.e., compound event), the specific term Natech applies (Krausmann et al., 2017; Showalter and Myers, 1994). A technological hazard can be the sole negative impact of a trigger (e.g., a combination of average physical processes), but could also amplify its overall consequences, and itself interact and initiate multiple negative impacts (UNDRR, 2019; Pescaroli and Nones, 2016).

A Natech is both trigger- and process-specific, in the sense that it depends on the characteristics of the trigger (e.g., flood, strong wind), the characteristics of the components of an industrial process and the hazardous materials involved. The consequences of a Natech (e.g., adverse health effects, damage to infrastructure, disruption of services, environmental degradation, business interruption, higher costs, economic loss) may be far-reaching (e.g., regional power outages, increase in global prices) and transboundary (UNDRR, 2019; Pescaroli and Nones, 2016). This is the case of critical infrastructure that societies increasingly rely upon for the continued provision of services (e.g., water, energy). Negative impacts that occur in one country and affect others, spillover effects, may be responsible for a welfare loss of ca. 20% due to the interconnected global economy (Feyen et al., 2020).

The development of new industrial and military sites, their aging, changing characteristics and location, allied to a possible change of climate-related natural hazards with global warming, may significantly alter Natech risk and the risk of failure of critical infrastructure, which may come at great cost to societies (EC, 2020a; Krausmann et al., 2016b). For example, assuming that GHG emissions will continue at the present rate, annual damage to critical infrastructure in Europe may reach ca. €34 billion by the end of the century (EC, 2020a).

3 Natural hazards and climate change as a security threat

Security has been the subject of numerous definitions over the years, in this study it is used with two meanings. It mainly refers to “the preservation of the norms, rules, institutions and values of society” (Makinda, 1998) in the global arena (i.e., international security), but is also used to refer to the access to an essential good, in this case preceded by the name of a resource (e.g., water security). Security spans across multiple sectors, for example information and communication technologies can challenge public security (CEU, 2010) as shown by the role of social networks in the violence in Myanmar in 2017 (Fink, 2018). In the context of natural hazards and climate change, it is important to understand what their implications are for security, and ultimately for defence (EEAS, 2020).

3.1 General context

For a number of years, the security implications of climate change have raised concerns within the EU and a link between the two has been strongly advocated (e.g., BMU, 2002; EEAS, 2014). However, in some cases, implications for security only materialize or become severe when there are already other aggravating factors at play, such as existing socio-economic pressures (e.g., weak institutions and governance), demographic pressure (e.g., rapid population growth; Kelley et al., 2015), lack of resilience (the ability to cope with shocks and adapt to change) and solidarity. This situation exists essentially when there is an inability to manage resources and disasters, to resolve conflicts, an overreliance on primary sectors (farming, hunting, fishing, logging and mining) and tourism, and limited capital (Barnett and Adger, 2007; Barrie et al., 2015; CEU, 2020; EEAS, 2014; Meyer et al., 2021; Rüttinger et al., 2015; UNDRR, 2019; UNSG, 2009, WB, 2010). Figure 3, illustrates some possible causal links between climate change and armed conflict (WB, 2010).

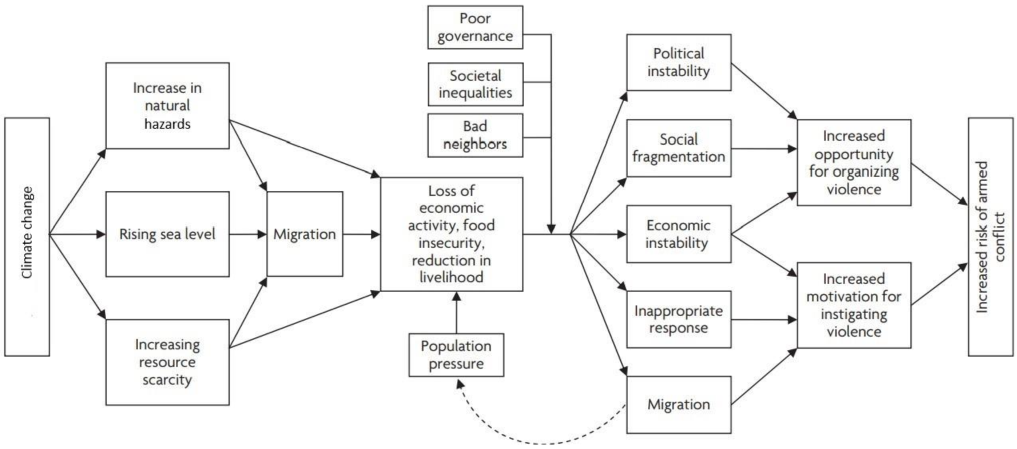

Figure 3. Possible pathways from climate change to conflict (adapted from the WB, 2010).

Knowing that some of the most fragile states in the world are highly exposed to climate change, and that threats may easily even spill over or affect ongoing or planned military operations, the link between climate change and security seems plausible (Figure 4; Bunde et al., 2020). However, this in no way should be an excuse to treat the most vulnerable and disadvantaged as threats, but rather as threatened groups in need of assistance and climate change adaptation (Thomas and Warner, 2019). For Europe, in the scope of ongoing EU *Common Security and Defence Policy* (CSDP) missions, the Horn of Africa and Sahel regions, and Mozambique (e.g., insurgency in Cabo Delgado) ([10]), spark increasing concern (Meyer et al., 2021).

([10]) Ahmed, K. (2021). Mozambique insurgency: 20,000 still trapped near gas plant six weeks after attack. The Guardian (accessed 1 July 2021). https://www.theguardian.com/global-development/2021/may/07/mozambique-insurgency-20000-still-trapped-near-gas-plant-six-weeks-after-attack

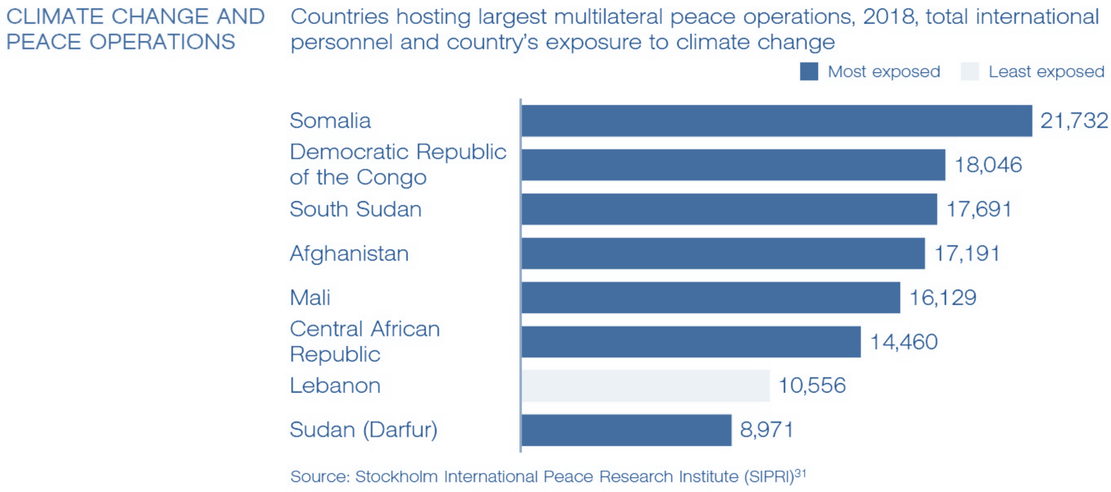

Figure 4. Total international personnel deployed for peacekeeping operations and exposure of hosting country to climate change (based on the illustration in Bunde et al., 2020).

Statistics may reveal some of the implications of climate change for security: from 2008 to 2016, over 20 million people/year have been forced to migrate due to extreme weather (WEF, 2020). In 2017, floods accounted for 8.6 million displacements worldwide, storms 7.5 million, and drought 1.5 million (UNDRR/CRED, 2018). In addition to the 2 million people that arrived at European shores (EC, 2020a) ([11]), climate refugees may migrate to Europe, which may be of concern. History also provides some examples of security issues:

- Syria's civil war in 2011, with involuntary migration to neighbouring states and Europe (CCS, 2020), was exacerbated by rapid population growth ("from 5 million in 1960 to 22 million in 2008" according to IPCC, 2018), drought, mismanagement of water and food shortages (Karnieli et al., 2019; Kelley et al., 2015; Trigo et al., 2010), but also exacerbated by specific situations such as the diversion and damming (South-eastern Anatolia Project) of the Euphrates River by upstream Turkey (Karnieli et al., 2019);
- Tensions between Egypt and Ethiopia are being fuelled by the prospect of further water scarcity, food shortages and the control over river flows associated to the construction of the Grand Ethiopian Renaissance Dam, as 90% of Egypt's water usage comes from the Nile (Fantini, 2020; CCS, 2020);
- The civil war in Yemen in 2014 was sparked by water scarcity, over-extraction of groundwater and price volatility (Douglas, 2016);
- Strained relations between India and Bangladesh due to involuntary migration, are mostly driven by salt contamination of soil and decrease in crop production in Bangladesh, and exacerbated by natural hazards and climate change (Chen and Mueller, 2018).

The weaponizing of the environment by state and non-state actors is also common. For example, in 1938 the dike of Huayuankou on the Yellow River in China was destroyed by tunnelling to halt the advance of Japanese forces; in 2011, Al Shabaab sabotaged food aid during Somalia's civil war and famine, a country that was struggling with severe drought; or, in 2016, water facilities were bombed in Yemen by Saudi Arabia. The seizing of resources has also been used as means of legitimization, for example, in 2014 the Islamic State halted water flows in Iraq (i.e., Mosul Dam) and Syria (i.e., Tabqa Dam).

Climate change is, therefore, considered a 'threat multiplier' (CNA Corporation, 2007) since it interacts with other factors to exacerbate or create new sources of instability and conflict. This evolving security environment poses numerous challenges (e.g., infrastructural, logistical, intelligence, resources, force protection; Briggs, 2020) to operations, strategy, tactics and military roles (e.g. towards more humanitarian assistance) and may ultimately affect the structure and composition of the military through, for example, "base realignment and closure" (Barrie et al., 2015; New Zealand Ministry of Defence, 2018).

([11]) United Nations High Commissioner for Refugees. Operational portal, Refugee situations: Mediterranean situation (accessed 1 July 2021). https://data2.unhcr.org/en/situations/mediterranean#_ga=2.35247465.917801613.1584978224-%20817118242.1583678580

New security threats may also undermine military capability by creating an additional burden. For example, the military may be requested to respond more frequently to climate-related disasters, provide humanitarian assistance, logistics and sanitation aid, or perform stability or search and rescue operations, at home or abroad, stretching resources and decreasing military capability (Briggs, 2020; Brock et al., 2020; IRIS, 2014; New Zealand Ministry of Defence, 2018; Scott and Khan, 2016). These threats may also produce additional pathways for hybrid threats.

In Figure 5, the implication of natural hazards and climate change are presented based on several studies (Barnett and Adger, 2007; Briggs, 2020; Bunde et al., 2020; EEAS, 2014, 2020; EC, 2019a; *European Parliament resolution 2012/2095(INI)*; BMU, 2002; Mosello et al., 2019; Nett and Rüttinger, 2016; *Paper from the High Representative and the European Commission to the European Council*, S113/08; Rüttinger et al., 2015; CCS, 2019; UNSG, 2009; UNSC, 2011).

Figure 5. Security implications of climate change.

These threats, and their multiplication, will bring additional uncertainty and complexity to military planning and operations, due to changing environmental conditions and socio-political landscapes.

In addition, climate policy is not exempt of its own security risks. There may be unintended effects associated to an ecological transition that could reshape geopolitics and the job market. A good example are the yellow jackets protests in France in 2018, sparked by the indiscriminate implementation of a climate tax to fuels, affecting for example rural communities that have no alternative but to use fuels for their living. On the other hand, climate denial can delay action, in the case of the military this means effective climate change mitigation and adaptation, in other words a delay in accounting for climate change in operations and strategy or approving investment in capabilities and infrastructure (Briggs, 2020; GAO, 2014). Finally, natural hazards may also become fertile ground to gain public support, raise funds and recruit new militants to extremist organizations, for example the Jamaat-ud-Dawa terrorist organization in the 2005 earthquake-hit areas of Pakistan.

3.2 Challenges and opportunities of a changing Artic

The Artic experiences more rapid warming than the world's average (AMAP, 2017; Thoman, 2020) – a phenomenon called Artic Amplification. Since 2014, Arctic annual surface air temperatures have exceeded those from 1900 to 2013 (AMAP, 2019; Thoman, 2020). In most of the ice-free Arctic Ocean, the August mean sea surface temperature has been following an increasing trend since 1982 (Thoman, 2020), sea ice thickness declined by 66% over six decades (AMAP, 2017; Kwok, 2018), and record lows of Artic sea ice extent were registered from 2015 to 2018 (AMAP, 2019; Thoman, 2020). Projections suggest that the Artic may be ice-free in the coming decade, during summer (Peng et al., 2020). Over land, permafrost has warmed on average 0.29°C from 2007 to 2016 and the thawing layer above it (i.e., the seasonal active layer, which can be several decimetres to a few meters deep; Anisimov and Reneva, 2006) has deepened for the same period (AMAP, 2017; Biskaborne et al., 2019). Furthermore, due to past emissions and ocean heat storage, most of these trends will continue even if GHG emissions are cut.

These changes that are already taking place in the Artic, present opportunities to local communities and states, particularly those with territories in the Artic (Canada, Denmark, Finland, Iceland, Norway, Russia, Sweden and the US); but, at the same time, they present significant threats to security and defence, due to developing geopolitical interests, natural hazards and cascading effects.

The expansion of the open-water season in the Artic creates new opportunities for shipping and trade (AMAP, 2017; Barnhart et al., 2016; Brock et al., 2020; IPCC, 2018; UNSG, 2009), as some routes between Asia, Europe and North America become available and more competitive with reduced travel times and fuel needs. The Northeast Passage, including the Northern Sea Route, and the Northwest Passage (see Figure 6) have been experiencing an increase of activity over the last decade, mainly by oil and gas tankers (Zandee et al., 2020). A longer open-water season also opens the possibility for cruise tourism and, in conjunction with changes in ocean temperature, phytoplankton and the northern expansion of fish stocks (e.g. mackerel, cod; Haug et al., 2017; IPCC, 2018), the opportunity for commercial fishing. **All these activities may lead to disputes over maritime sovereignty and passage rights.** At the same time, as sea ice becomes more mobile, and activities in the Arctic Ocean intensify, ice-related hazards become more likely (AMAP, 2017), possibly demanding more services such as icebreaking assistance, search and rescue, as well as prevention, containment and response to hazardous spills. This is an additional burden that may also undermine military capability.

Finally, the Arctic is estimated to have ca. 13% of global undiscovered oil and a third of global undiscovered gas, of which 84% is expected to be found offshore (Stauffer, 2009) (see Figure 7). It is also known to have large mineral deposits (e.g., rare earth elements, metals such as gold, iron, zinc and platinum, and uranium in Greenland) and coal (Brock et al., 2020). A changing Artic means that shared or un-demarcated resources, both inland and offshore (AMAP, 2017; Stang, 2016; Brock et al., 2020; Suter et al, 2019; UNSG, 2009; Zandee et al., 2020), may become more accessible, which may lead to competition and territorial disputes (EC, 2008, 2016b; Brock et al., 2020; Scott and Khan, 2016; Soare, 2020; Wezeman, 2012).

Some reports, however, argue that increasing competition and potential for conflict is unlikely, since, for example, most fish stocks and hydrocarbon reserves are within undisputed exclusive economic zones (Stang, 2016; Zandee et al., 2020). Others see the Artic as a challenge even if there are mechanisms (e.g., legislation, Artic Council) to settle disputes (Brock et al., 2020). The reality is that multiple states have updated their defence policies and increased their military capabilities in the Artic (Wezeman, 2012). The US, for instance, has pledged to develop infrastructure and capabilities (DOD, 2013; The White House, 2013, 2014; USDAF, 2020), enhance and explore additional military training, exercises, crisis gaming, and combined deployments, perhaps because the Artic also hosts "critical launch points for global power projection" (USDAF, 2020).

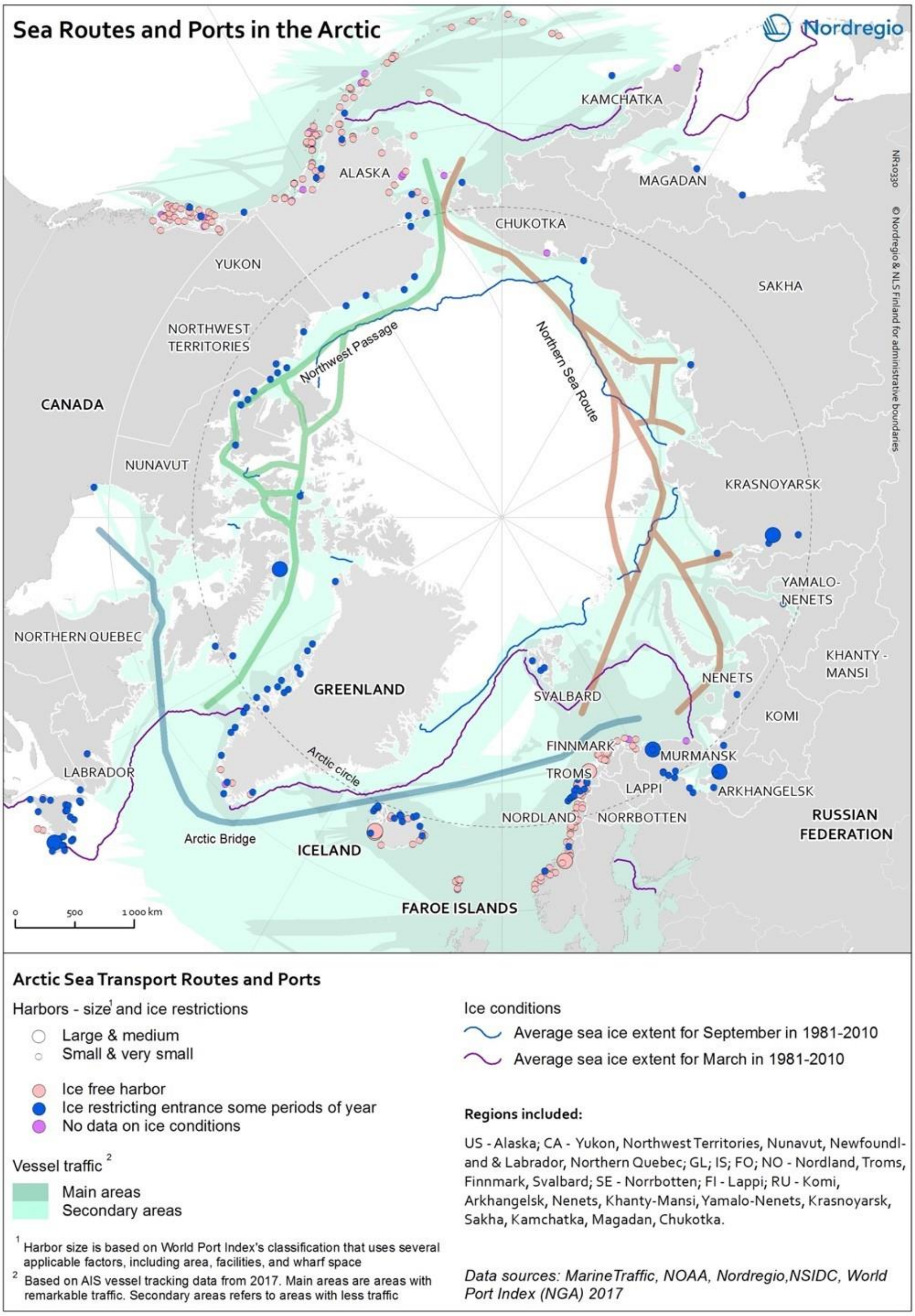

Figure 6. Artic open-water season shipping and trade routes (Turunen, 2019a). Source: Eeva Turunen/Nordregio at www.nordregio.org

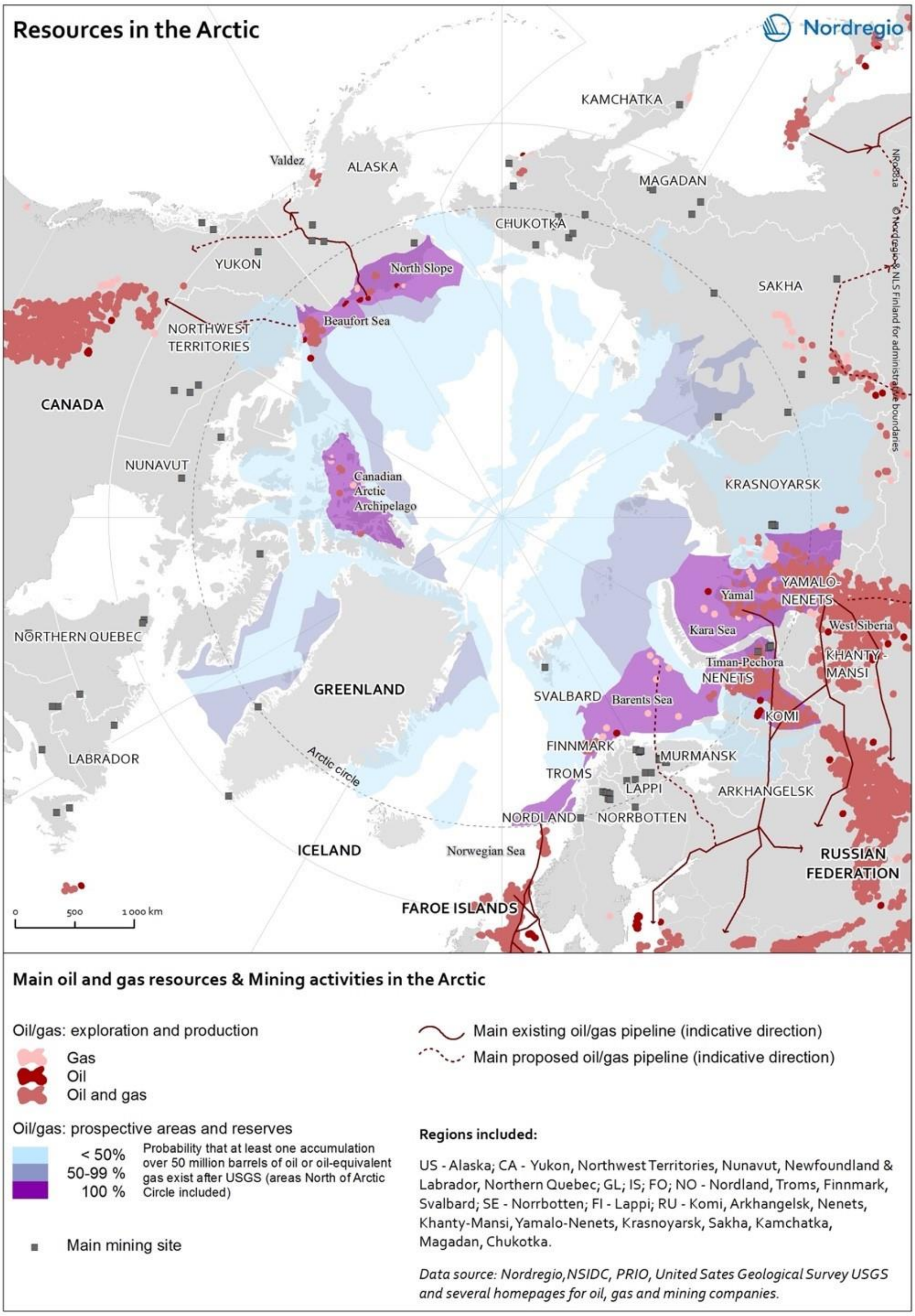

Figure 7. Estimate of hydrocarbon resources and mining sites in the Artic (Turunen, 2019b). Source: Eeva Turunen/Nordregio at www.nordregio.org

3.3 The concept of hybrid threats

Hybrid threats is an overarching term referring to coercive, subversive, conventional and unconventional actions, perpetrated by state or non-state actors in a coordinated manner, to exploit weaknesses or generate ambiguity, while maintaining deniability, with the purpose of gaining advantage (CEU, 2019; EC, 2016c, 2018; Giannopoulos et al., 2020).

Hybrid threats can undermine trust, change perception and opinion, deepen polarization, confuse situational awareness and intelligence, and increase pressure, thereby compromising policy and decision-making. They can be used to deplete resources (e.g., water diversion), trigger expenditure (e.g., violation of airspace), destabilize and lay the groundwork for further action (Giannopoulos et al., 2020).

This covert warfare can become more prominent and severe as dependencies on infrastructure and technology, interconnectedness and complexity in our societies continue to grow. This creates new opportunities for exploitation that are both affordable, far-reaching and enable anonymity (e.g., computing power, big data and artificial intelligence). For example, a hybrid attack to a critical infrastructure (e.g., power plant), on which a community heavily relies upon, may cause significant disruption and damage at various levels, considering that its effects may cascade to other sectors.

Some of the tools used in hybrid threats include, but are not limited to, disinformation, cyberattacks, espionage, sabotage, vandalism, control of assets and resources, foreign investment, terrorism, chemical, biological, radiological and nuclear contamination (Giannopoulos et al., 2020). **Natural hazards and climate change create or exacerbate existing weaknesses, possibly opening new opportunities for hybrid attacks**, for example with the objective to decrease the ability to recover.

In fact, some of the examples of weaponizing of the environment provided in Section 3.1, could very well fit in the range of tools used in hybrid threats, with climate change exacerbating its effects (Kohler et al., 2019). Furthermore, in conflict areas (e.g., UNEP/UNCHS, 1999), but also in disaster zones, there is often a void of environmental information (e.g., pollution monitoring), which may enable the spreading of disinformation.

4 Defence infrastructure in a changing environment

4.1 The military footprint

In most states, the military are often structured in three specialized departments (e.g., the *Ministère des Armées* of France, the *Bundeswehr* of Germany, or the *US Department of Defense* [DOD]):

1. The Army, also known as land force;
2. The Navy, also known as naval force;
3. The Air (and Space) Force.

Landlocked countries are generally the exception, not having a navy, and some countries have additional departments such as special forces, reserve forces, homeland security. To fulfil their mission, each military department is supported by a number of services (e.g., command, training, testing, research, lodging) that are provided by distinct military installations.

A military installation can be permanent, semi-permanent or temporary (e.g., forward operating bases), and established within or outside the territory of a state (i.e., overseas military installations), being subject to the laws of the host state. Some *EU Member States* have overseas military installations, such as France (Djibouti, United Arab Emirates, Ivory Coast, Gabon, Senegal, Germany, Lebanon, Mali, Chad, Niger, Syria, Iraq and Jordan), Germany (France and US), Greece (Cyprus), Italy (United Arab Emirates, Djibouti, Afghanistan, Kuwait, Libya and US) and The Netherlands (Aruba, Curaçao and US), while outside the EU the largest operator of overseas military installations is the US.

At the multinational level, the EU does not have a permanent military structure. However, the CSDP may deploy military (national and multinational forces) or civilian missions, which may involve contingency basing, as set out in the *Treaty of Lisbon* (2007). Some *EU Member States* also contribute with personnel, equipment and resources to NATO missions and to *UN Peacekeeping* operations.

Box 4. A note on the scope of this study.

Even though EU overseas military installations, as well as military operations in the context of multinational cooperation, may be negatively impacted by natural hazards and climate change, they are not addressed in this study.

4.2 Military installations

Military installations are the backbone of operational readiness. They support testing, maintenance and deployment of weapons systems, training and mobilisation of combat forces, combat operations, as well as staging platforms for humanitarian assistance and more (Marqusee et al., 2017). A site under a military installation can be contiguous or outlying and include any camp, post, station, yard, range, harbour, airfield, and so on.

Besides personnel, each military installation houses facilities, military assets, hazardous materials (e.g., chemical substances such as fuels and lubricants, ammunition, explosives) and non-hazardous supplies (subsistence, clothing, medical, construction, personal and repair) of different types and in different quantities.

Military installations (Figure 8) also **extensively use, and depend on, community infrastructure** (e.g., roads, bridges, medical facilities) and services (e.g., energy, water). For example, since 1988, the DOD has transferred ownership, operation and responsibility over utility systems to civilian entities due to competing funding priorities and cost savings, and in 2019, 614 out of 2590 utility systems have been privatised (GAO, 2020b).

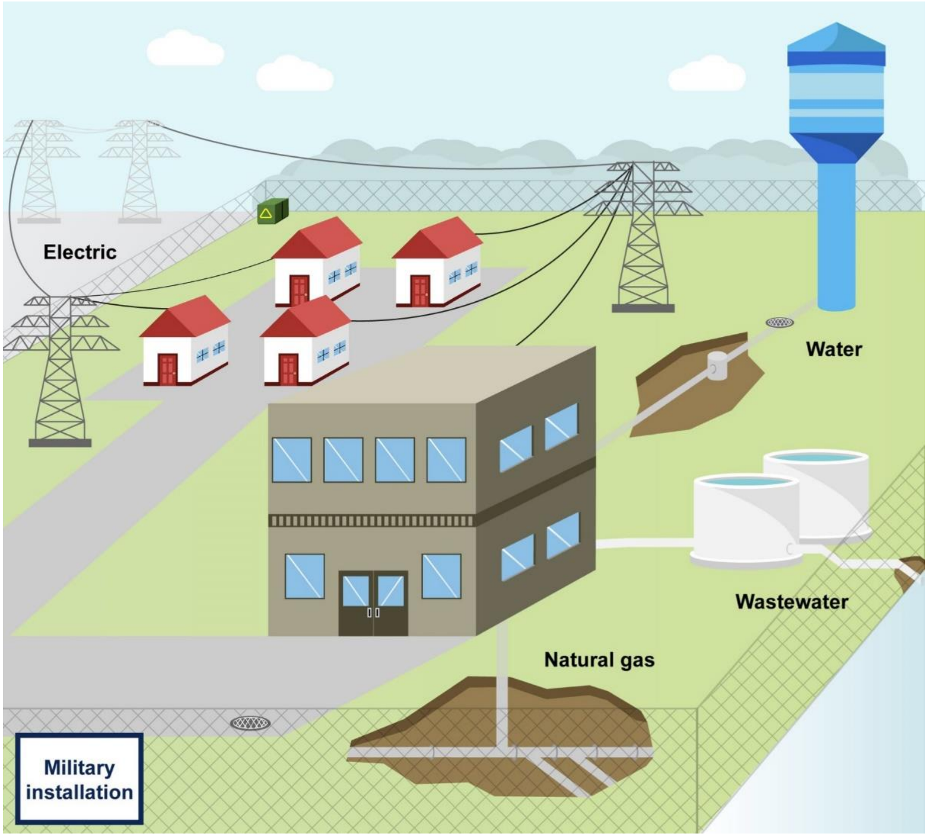

Figure 8. Illustration of a military installation, infrastructure and services that could be civilian owned and operated, both on-site (e.g., easement, right of way) and off-site (GAO, 2020b). Source: GAO-20-104/GAO

Military installations can be negatively impacted by natural hazards and climate change directly to their facilities, equipment they house or personnel, or through impacts on community infrastructure and services that they depend on (GAO, 2020a) – via cross-sector dependencies. Adding to this, the overall negative impacts can be exacerbated by the triggering of technological accidents due to the extensive use of hazardous materials. For example, ammunition and explosives are stored in above-ground or earth-covered magazines (DOD, 2019b), Petroleum/Oil/Lubricant (POL) and other chemicals (DOD, 2019e) are stored in storage tanks, oil and gas pipelines and distribution systems (DOD, 2021b) etc., even though they are in general subject to more strict regulations (DOD, 2019b, e, 2021).

Natural hazards and climate change can have significant direct negative impacts on weapons systems, which in turn can lead also to technological accidents (e.g., oil spill, fire, explosion). These, even though important to analyse, are not addressed in this study.

4.3 Cross-sector dependencies

Cross-sector dependencies, mapped in Figure 9, are all the community infrastructure and services (i.e., external civilian sources) that a military installation relies upon in order to fulfil its mission at home or overseas.

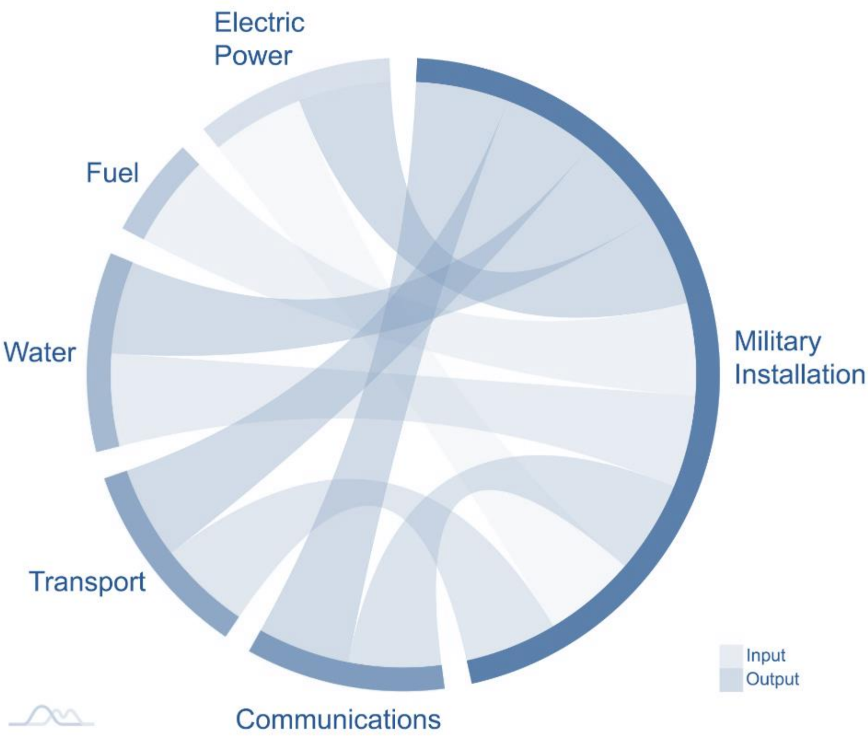

Figure 9. Map of potential uni-directional and bi-directional cross-sector dependencies of a military installation.

The relation between the military and the external contractors can be unidirectional (e.g., fuel) or bidirectional, in the sense that military installations are only receivers or both receivers and suppliers. In Figure 9, Electric power is marked as bi-directional because there might be the case where a military installation owns and operates power generation infrastructure and may feed surplus power to the commercial grid. Water is marked as bi-directional if we take into consideration water supply (input) and wastewater (output).

Some of the infrastructure and services, owned and operated by external contractors especially, can be outlying and cross borders, entering different jurisdictions (e.g. EU electricity interconnections). Furthermore, military installation cross-sector dependencies are more than just a uni-directional or bi-directional connection to a lifeline. There is (inter)dependency between utility systems, for example a hydrothermal power plant needs water to function, and facilities need more than one lifeline connected in general, for example a fuelling facility does not only receive fuel, but it cannot function without electricity, water and sewerage (DOD, 2020a). An analysis of indirect negative impacts on military installations, such as power outages or water shortage, that originate in cross-sector dependencies, needs to be conducted as a complex network problem of interdependent critical infrastructures from asset-level to system-of-systems with different vulnerabilities (e.g., Galbusera and Giannopoulos, 2016; Piccinelli and Krausmann, 2017; Stergiopoulos et al., 2016; Szinai et al, 2020).

Table 1 describes some of the possible damage types induced by natural-hazards on military installations cross-sectors dependencies, namely vulnerable components of power grids, fuel and water supply. The table was produced based on the guidelines produced by the *American Lifelines Alliance* (ALA, 2005a, b, c), the Commission Staff Working Document on adapting infrastructure to climate change (EC, 2013), the methodology for multi-hazard loss estimation produced by the *US Federal Emergency Management Agency* (FEMA, 2018, 2020, 2021a, b); and on the multiple studies produced by the JRC (Girgin and Krausmann, 2015; Kern and Krausmann, 2020; Krausmann, 2011, 2014; Karagiannis et al., 2017, 2019a, b; Krausmann et al., 2013, 2014, 2015, 2016a, b; Krausmann and Mushtaq, 2006; Necci et al., 2018, 2019; Piccinelli and Krausmann, 2013, 2015; Vamanu et al., 2021).

Table 1. Examples of possible damages induced by selected natural hazards to military cross-sector dependencies, namely the power grid, fuel and water supply.

	Forces exerted on structures and processes	Load parameters / Intensity measures	Failure mechanism (cause)	Damage state (end-state)	Vulnerable components		
					Power grid	Fuel supply	Water supply
Extreme heat	Thermal load.	Temperature.	Rapid increase in power demand for cooling (e.g., Zscheischler et al., 2020), overheating, overpressure.	Bending, creep, loss of power generation efficiency and capacity, loss of power transmission and distribution efficiency (e.g., Añel et al., 2017), loss of throughput capacity in gas pipelines, leak, water contamination (e.g., bacterial and algal growth).	Power plants, transmission substations, transmission lines, distribution substations, distribution lines, transformers (e.g., Gao et al., 2018).	Transmission and distribution pipelines.	Reservoirs, transmission and distribution pipelines, water service laterals, storage tanks, water treatment facilities, pump stations.
Extreme cold	Thermal, snow, rain-on-snow, ice and impact (e.g., branches, avalanche) and static loads (glaze).	Temperature, time-of-frost, time-of-wetness, amount-of-frozen-water, freeze/thaw cycles, winter index (e.g., Corvo et al., 2008; Kočí et al., 2017).	Rapid increase in power demand for heating, excessive catenary loading, thermal shock, frost heave, glazing, ice shedding, ice jacking, thermal contraction damage, fatigue.	Sinking (e.g., roof), topple, Fracture, buckling, collapse, damage from collapsing parts, electrical fault, malfunctioning, ignition and permanent damage, wear, power outage, leak.	Control, protection and communication systems, transmission substations, transmission lines, transmission and communication towers, distribution poles, distribution substations, distribution lines, transformers.	Transmission and distribution pipelines.	Canals, storage tanks, water treatment facilities, water diversion structures, pump stations, electronic equipment.
Floods (¹)	Hydrostatic (including buoyancy), hydrodynamic (including uplift and load reversal), wave, impact (including debris, floating equipment, ice) and settlement loads, pore pressure.	Discharge, water depth, velocity, duration, drag force, total energy (Bernoulli), Froude number, momentum flux, significant wave height, time-of-wetness (e.g., FEMA, 2018; Macabuag et al., 2016; Nofal et al., 2020).	Excessive loading from water and debris action, fatigue, erosion (including scour, seepage, pipping, cavitation), abrasion, loss of bearing capacity, relaxation (e.g., bolts), clogging, condensation, corrosion, ignition by mechanical (friction, grinding or impact) sparks.	Uplift and displacement (including roll-over, overturn, sinking, sliding), tilting, toppling, bending, buckling, fracture, collapse, sliding, loosening, impact damage from floating debris or equipment, damage from collapsing parts, electrical fault, malfunctioning, power outage, ignition and permanent damage, overflow (e.g. sewer, sump), wear, leak, contamination, fire.	Power plants, control, protection and communication systems, transmission substations, transmission lines, transmission and communication towers, distribution poles, distribution substations, distribution lines, transformers, electronic equipment.	Control systems, stations, transmission and distribution pipelines, storage tanks, processing facilities, pump, compressor and pressure regulating and metering stations, service connections.	Wells, canals, transmission and distribution pipelines, water service laterals, storage tanks, water treatment facilities, water diversion structures, pump stations, electronic equipment.
Drought	Settlement load.	—	Decrease in water availability, subsidence, loss of bearing capacity.	Loss of power generation capacity, power outage, loss of water supply, loss of cooling capacity.	Power plants.	Transmission and distribution pipelines.	Transmission and distribution pipelines, water service laterals.

Table 1. (continuation).

	Forces exerted on structures	Load parameters / Intensity measures	Failure mechanism (cause)	Damage state (end-state)	Vulnerable components		
					Power grid	Fuel supply	Water supply
Windstorms	Wind and impact loads (e.g., projectiles).	Wind speed, pressure and force (e.g., FEMA, 2021a, b; Prahl et al., 2015), kinetic energy of projectiles.	Excessive loading from wind and debris action, sloshing, relaxation (e.g., bolts), fatigue, erosion, abrasion, ignition by mechanical (friction, grinding or impact) sparks, suspension of particulate matter, clogging.	Uplift and displacement (including roll-over, overturn, sliding), tilting, toppling, bending, collapse, impact damage from airborne and ground-level debris or equipment, damage from collapsing parts, electrical fault (e.g., phase to earth or phase-to-phase short circuit, open-circuit), malfunctioning, power outage, release of hazardous materials, contamination, ignition.	Power plants, control, protection and communication systems, transmission substations, transmission lines, transmission and communication towers, distribution poles, distribution substations, distribution lines, transformers.	Transmission pipelines, storage tanks.	Storage tanks, water treatment facilities, water diversion structures, pump stations, electronic equipment.
Lightning	Thermal, electrical, mechanical and impact loads (e.g., projectiles).	Peak current amplitude, flash charge, specific energy, polarity, number of strokes, flash duration, induced voltage.	Overvoltage, overheating, electromagnetic pulse, elecgromagnetic induction, surface explosion, corrosion, ignition.	Electrical fault, malfunctioning, permanent damage (e.g., windings, circuit boards), decapping, shielding failure, line tripping, abnormal oscillation, frequency collapse, fracture, buckling, puncturing, damage from airborne debris, leak, ignition, explosion, wear.	Control, protection and communication systems, transmission substations, transmission lines, transmission and communication towers, distribution poles, distribution substations, distribution lines, transformers, electronic equipment.	Control systems, transmission pipelines, storage tanks.	Storage tanks.
Wildfires	Thermal and ash loads.	Heat radiation, engulfment ratio, mass of ash accumulated per m^2.	Flame impingement, ember attack, fire spread, overheating, clogging, corrosion, ignition (including ember attack).	Fire damage, damage from airborne debris, creep, wear, water contamination with ash.	Power plants, control, protection and communication systems, transmission substations and lines, transmission and communication towers, distribution poles, substations and lines, transformers, electronic equipment.	Control systems, pump stations, transmission and distribution pipelines, storage tanks, processing facilities, compressor and pressure regulating and metering stations, service connections.	Reservoirs, transmission and distribution pipelines, water service laterals, storage tanks, water treatment facilities, pump stations.
Landslides	Impact and static (debris flow deposit) loads, settlement load.	Deposition height, debris flow height, velocity, impact, permanent ground displacement (e.g., FEMA, 2020; Sterlacchini et al., 2014; Zugić et al., 2018).	Excessive loading from debris action.	Displacement (including roll-over, overturn, sliding), tilting, toppling, bending, buckling, fracture, collapse, leak.	Power plants, transmission substations, transmission lines, transmission and communication towers, distribution poles, distribution substations, distribution lines, transformers.	Transmission and distribution pipelines, storage tanks, pressure regulating and metering stations, service connections.	Wells, canals, tunnels, transmission and distribution pipelines, storage tanks, water treatment facilities, water diversion structures, pump stations, service connections.

Table 1. (continuation).

	Forces exerted on structures	Load parameters / Intensity measures	Failure mechanism (cause)	Damage state (end-state)	Vulnerable components: Power grid	Vulnerable components: Fuel supply	Vulnerable components: Water supply
Thawing permafrost	Settlement load.	—	Thaw settlement, erosion, loss of bearing capacity.	Displacement (including sinking, overturning, sliding), tilting, toppling, bending, fracture, collapse, damage from ground-level debris and collapsing parts, leak.	Power plants, transmission substations and lines, transmission and communication towers, distribution poles, substations and lines, transformers.	Transmission and distribution pipelines, storage tanks, pressure regulating and metering stations, service connections.	Wells, canals, tunnels, transmission and distribution pipelines, storage tanks, water treatment facilities, water diversion structures, pump stations, service connections.
Earthquakes	Seismic and settlement loads.	Peak ground acceleration, velocity and displacement, permanent ground displacement, Arias intensity, duration (e.g., Cao and Ronagh, 2014; FEMA, 2020; Nguyen et al., 2020).	Excessive loading from ground movement and shaking, structural pounding, fatigue, sloshing, relaxation (e.g., bolts), loss of bearing capacity, abrasion, hydraulic transients, ignition by mechanical (friction, grinding, impact) sparks, soil liquefaction.	Displacement (including sinking, overturn, sliding), tilting, toppling, bending, buckling, ratcheting, fracture, collapse, loosening, damage from collapsing parts, leak, electrical fault, malfunctioning, ignition and permanent damage.	Power plants, control, protection and communication systems, transmission substations and lines, transmission and communication towers, distribution poles, substations and lines, transformers, electronic equipment.	Control systems, pump stations, transmission and distribution pipelines, storage tanks, processing facilities, pump, compressor and pressure regulating and metering stations, service connections.	Wells, canals, tunnels, boilers, reactor, transmission and distribution pipelines, storage tanks, water treatment facilities, water diversion structures, pump stations, service connections.
Volcanic activity	Thermal, settlement, impact and static (tephra deposit) loads.	Kinetic energy of projectile, mass of ash accumulated per m^2.	Overheating, excessive loading from debris action, clogging, corrosion, ignition (including magma).	Sinking (e.g. roof), damage from airborne debris, creep, bending, buckling, fracture, leak, wear, water contamination with ash.	Power plants, control, protection and communication systems, transmission substations and lines, transmission and communication towers, distribution poles, substations and lines, transformers, electronic equipment.	Control systems, pump stations, transmission and distribution pipelines, storage tanks, processing facilities, compressor and pressure regulating and metering stations, service connections.	Wells, canals, tunnels, transmission and distribution pipelines, storage tanks, water treatment facilities, water diversion structures, pump stations, service connections.
Space weather	Electrical load.	Geomagnetically Induced Currents (GICs)	High reactive power consumption, half-cycle saturation, injection of harmonics, magnetic stray fluxes, overheating, vibration, corrosion.	Transformer saturation, reactive power loss, electrical equipment tripping (e.g., transformer, relay, Static Var Compensator, shunt reactors, power lines), electronic fault (e.g., control, computer storage), malfunctioning, ignition and damage (e.g., windings), fracture, wear, voltage collapse, power system instability (e.g., voltage fluctuation) and failure, power outage.	Control systems, transmission substations and lines, transformers.	Control systems, transmission pipelines.	Transmission pipelines.

([1]) Including tsunamis.

4.3.1 Electric power

The military require reliable electrical power for installations and equipment to function. Electricity is necessary to conduct operations (operational power), command and control, intelligence, surveillance, and reconnaissance, communications, R&D, testing and training, maintenance, medical support, emergency management etc. (DA, 2018).

When operations transition from offensive/defensive to stability, a shift from tactical to prime power systems occur. Tactical power is any power system with limited capacity (up to 200 kW) and distribution, but greater mobility. It includes, for example, individual power (e.g., batteries and power sources less than 1 kW), generators, fuel cells and more efficient micro-grids. On the other hand, prime power is any power system with more than 200 kW, including power plants and medium-voltage distribution lines up to several kilometres long, which fill the gap between tactical and utility power (DA, 2018).

For enduring locations, the tendency is to use sustained power systems by establishing contracts with domestic or foreign utilities and coordinate connections to the civilian power grid (DA, 2018). Military installations in the US rely almost entirely on utility power, and are often the largest consumer — 50 MW on average, of which ca. 40% are critical loads for mission assurance (Marqusee et al., 2017).

The transition to utility power creates a dependency on external sources, over which the military have limited control. This may entail a higher risk depending on how utility systems are managed and are open for cooperation (Marqusee et al., 2017). Military installations, especially those outlying, are experiencing more and longer outages than other utility costumers (Marqusee et al., 2017). Figure 10 presents the breakdown of the number of outages at US military installations for each defined outage duration group.

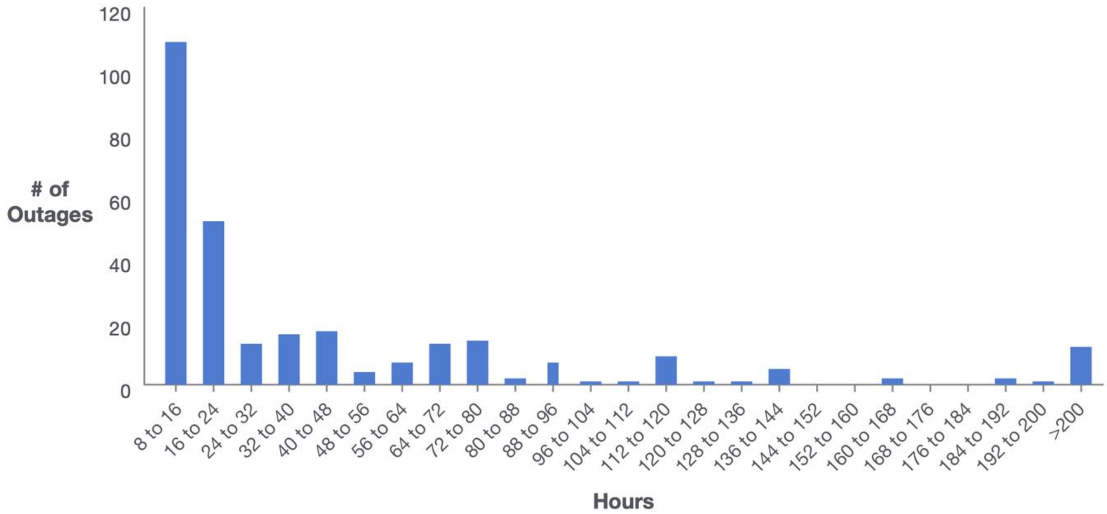

Figure 10. Outages at US military installations as a function of duration, from 2012 to 2014 (Marqusee et al., 2017). Source: Noblis Inc.

Outages of a few hours are not of major concern, even if they have a cost, but those that last days or weeks can jeopardize missions and operations, as well as create pathways for hybrid or other security threats (e.g., misinterpretation and escalation).

Infrastructure that generates and distributes power to critical loads, should be considered as defence critical infrastructure and should have stricter requirements, such as the minimization of single points of failure, introduction of redundancy and backup power to ensure both continuity and maintainability (DOD, 2019c).

4.3.2 Fuel

The military rely on fuel to power aircrafts, ships, tactical-vehicles and weapons systems, and to support troops in combat (e.g., forward operating bases). The DOD is responsible for operating fuel systems, including storage tanks and distribution pipelines, inside military installations, while private companies deliver, meter, and regulate pressure in the supply (DOD, 2021b). Figure 11 illustrates a fuel pipeline network, where the large volume costumer is generally a military installation.

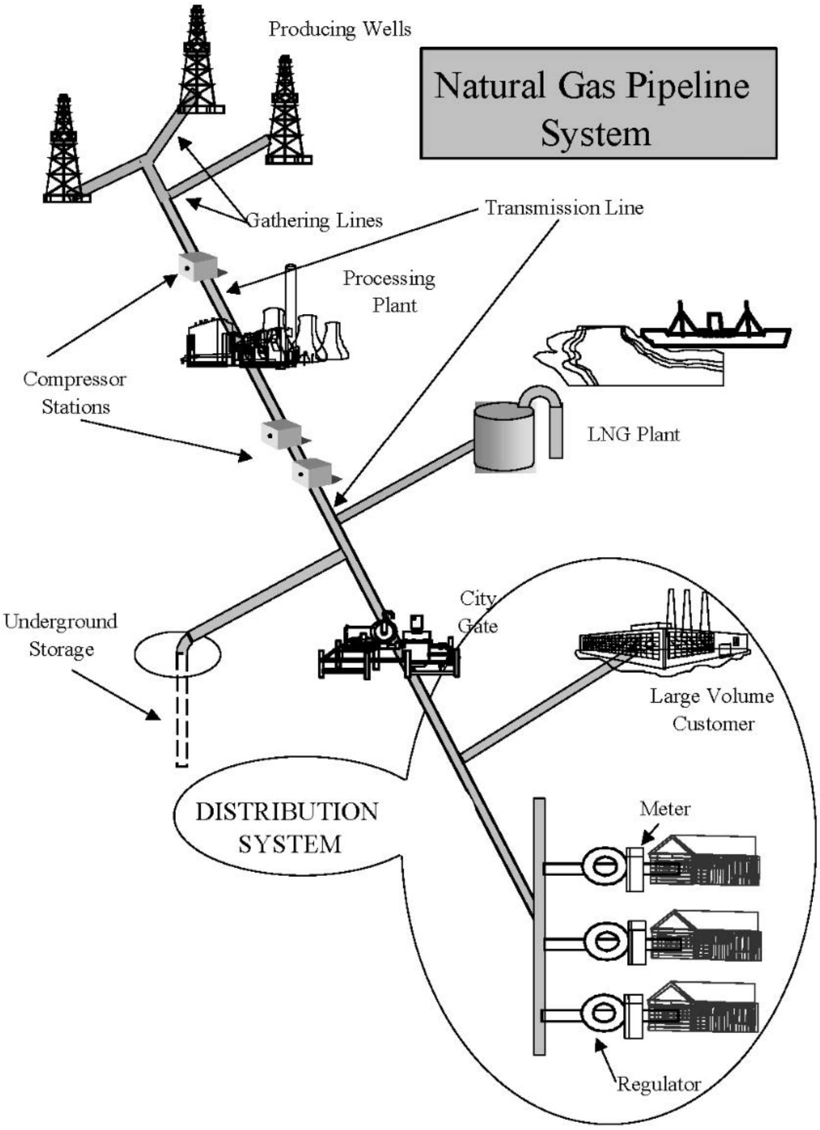

Figure 11. Illustration of a gas pipeline network, its facilities and components (DOD, 2021b). Source: UFC 3-430-05/DOD and the US Department of Transportation

Oil and gas can be distributed by vessel, road and rail. However, one of the preferred and safest transport methods of oil and gas, from production to refineries and storage, are pipelines (Cruz and Krausmann, 2013).

Fuel pipelines can be classified as dedicated inter-terminal pipelines, which may cross countries, public and private land, or commercial installation pipelines, which may not. These systems can be placed above- or underground, or underwater, and can supply different fuel grades from a bulk storage facility to military installation aircraft, marine or tactical vehicle fuelling facilities (DOD, 2020a).

Bulk fuel storage facilities are composed of bulk storage tanks, pipeline receiving, pumping and loading facilities, piping and system components. At one of these receiving facilities, fuels are separated and transferred to operating storage tanks that feature, among others, refuelling fill-stands and direct fuelling systems (hydrants) that keep fuel in continued circulation to provide smooth operation. In the case of aircrafts, large ones are typically fuelled directly, while the remaining are fuelled by truck. In the case of vessels, piers, wharves and offshore moorings – connected to underwater pipelines – are used to discharge or receive fuel. Tactical vehicles are generally fuelled in filling stations (DOD, 2020a).

Storage tanks, which can be of vertical or horizontal design, aboveground and underground, are typically used for bulk, operating, ground vehicle fuelling, product recovery, storage of contaminated fuel, jet engine test cell fuel and other miscellaneous uses, and their capacity is linked to the logistic and mission requirements of a military installation (DOD, 2020a).

4.3.3 Water

Drinking water at fixed military installations is commonly provided by a local utility that is owned by a civilian entity, such as a municipality or water company. In cases where that is not an option, the military may obtain their water from surface or ground sources directly, or through desalination, by building, operating and maintaining water infrastructure. Figure 12 illustrates the water infrastructure that can serve a military installation, with primary components being pumps, pipes and storage. Depending on the quality of the water, some installations may only require simple treatment such as chlorination (DOD, 2019d).

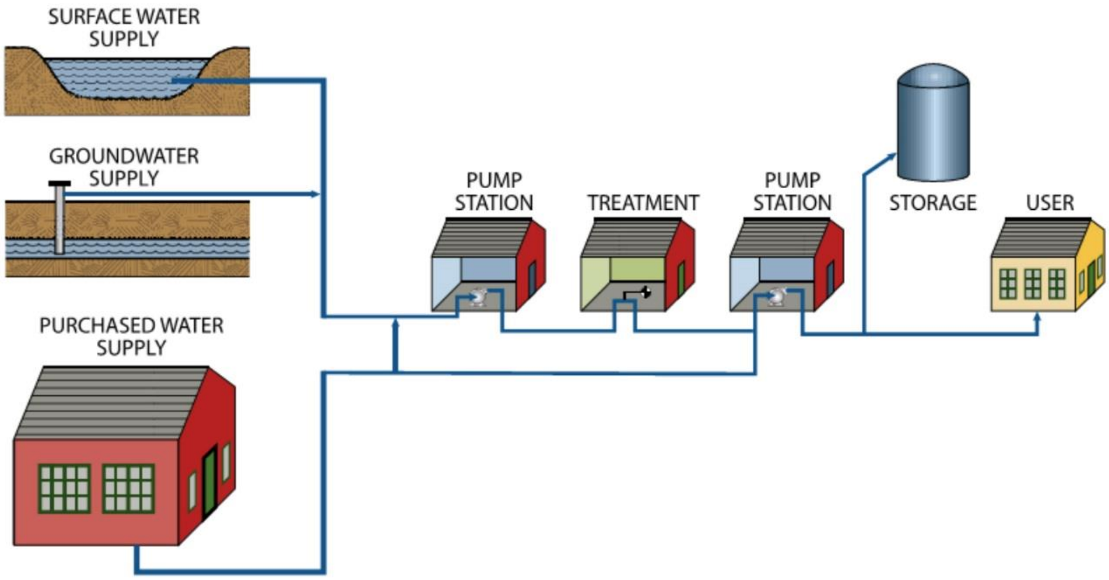

Figure 12. Configuration of a water supply system at a military installation. Source: UFC 3-230-02/DOD

Water is essential to a military installation, it is used in mission-critical facilities (e.g., airfields, ports) and equipment (e.g., boilers, cooling, fire suppression), but also for health and safety, and well-being. A number of activities such as maintenance, training and testing, R&D, medical services, hygiene and sanitation, food preparation, laundry, and irrigation rely on the availability of water (GAO, 2019). Clearly, water scarcity would significantly impair a military installation to effectively support operations.

4.4 Exposure to natural hazards and climate change

The DOD conducted a study across military departments to assess qualitatively their exposure to climate-related events (DOD, 2019a). The study looked into floods, drought, desertification, wildfires, and thawing permafrost. Data was collected in the form of questionnaires (see Table 2) for 79 critical military installations. The selection of military installations was based on criticality regarding mission assurance and operational role. No overseas military installations were considered.

Table 2. Example of questionnaire sent out to each US military department in the context of a DOD (2019a) study, to assess the present day (P) and 20 years expected (E) exposure of US critical military installations to climate-related natural hazards.

	Floods		Drought		Desertification		Wildfires		Thawing permafrost	
Military installation	**P**	**E**	**P**	**E**	**P**	**E**	**P**	**E**	**P**	**E**
Fort Greely	No	No	No	No	No	No	No	No	Yes	Yes

Box 5. A note on the DOD publication addressed in Table 2 (DOD, 2019a).

The study does not explicitly state which kind of climate-related natural hazards scenarios were provided to the US military departments, if any, in order to fill in the questionnaire.

4.4.1 Military installations

The DOD (2019a) revealed that **very few military installations are not presently exposed to any climate-related natural hazard** (Table 3). Some examples of military installations that are expected to be affected, or were already affected, by climate-related natural hazards include:

- Floods: US Joint Base Langley-Eustis, US Navy Base Coronado, US Air Force Base Offutt, US AFB Hill and US Naval Station Norfolk.
- Drought: US Joint Bases Anacostia-Bolling, US Joint Base Andrews, US Naval Observatory/Naval Support Facility, US Washington Navy Yard and US Naval Air Station Key.
- Desertification: US Army Camp Roberts and San Miguel, US Army White Sands Missile Range, US Air Force Bases Kirtland, US Air Force Base Creech, US Air Force Base Nellis and US Air Force Base Hill.
- Wildfires: US Air Force Base Vandenberg and US Navy Point Air Station Mugu Sea Range.
- Thawing permafrost: US Army Fort Greely.
- Windstorm: US Air Force Base Homestead, US Navy Camp Lejeune and US Air Force Base Tyndall.

Table 3. Summary of present day (P) and 20 years expected (E) exposure of selected US critical military installations to climate-related natural hazards. Red arrows highlight the projected increase in exposure (adapted from DOD, 2019a).

		Floods		Drought		Desertification		Wildfires		Thawing permafrost	
Military Departments	**#military installations**	**P**	**E**	**P**	**E**	**P**	**E**	**P**	**E**	**P**	**E**
US Navy	18	16	16	18	18	—	—	—	7 ↑	—	—
US Army	21	15	17↑	5	5	2	2	4	4	1	1
US Air Force	36	20	25↑	20	22↑	4	4	32	32	—	—
Other (1)	4	2	2	—	3 ↑	—	—	—	—	—	—
Total	79	53	60↑	43	48↑	6	6	36	43↑	1	1

(1) *Defense Logistics Agency*, *Defense Financing and Accounting Service* and the *Washington Headquarters Service*.

Regarding the state of US critical military installations in 20 years' time, the *US Navy* is expected to have more installations exposed to wildfires. The *US Army* and the *US Air Force* are expected to have more installations exposed to floods; and, the *US Air Force* is expected to have more installations exposed to drought. For the remaining cases, the exposure in 20 years' time does not differ from that identified in 2019.

US Navy installations are, and will continue to be, predominantly exposed to floods and drought, currently 89% and 100% of the selected ones, respectively. On the other hand, in 20 years' time, 39% will additionally become exposed to wildfires, a currently inexistent situation (see Figure 13). This actually represents the largest increase reported, among all the climate-related events and US military departments.

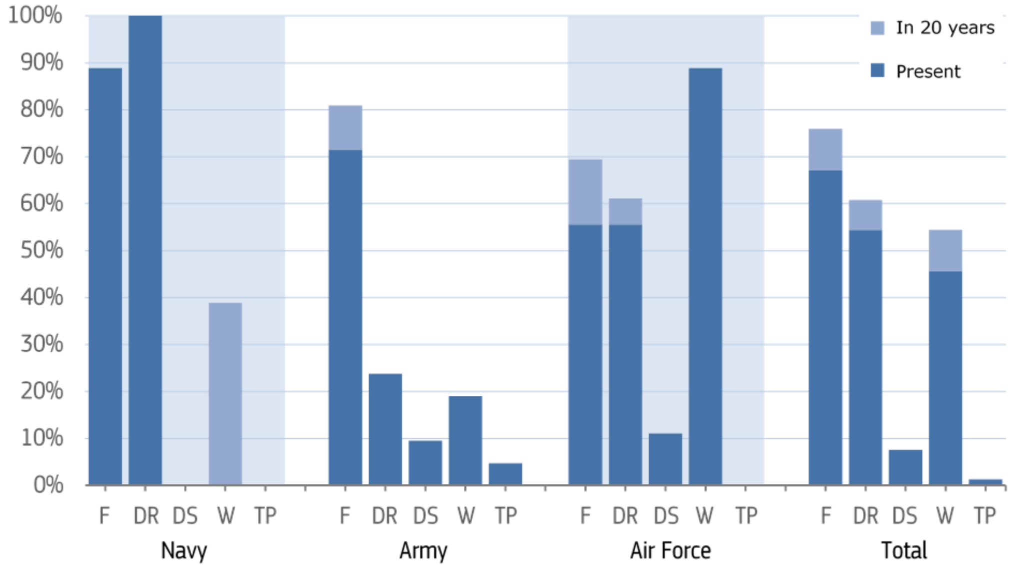

Figure 13. Breakdown by military department of the share of critical military installations that are currently exposed, or are expected to be exposed in 20 years' time to climate-related natural hazards (F – floods; DR – drought, DS – desertification, W – wildfires, TP – thawing permafrost). The rightmost panel corresponds to the overall share of critical military installations, irrespective of US military department (based on DOD, 2019a).

The *US Army* installations selected in the DOD survey are predominantly exposed to floods, 71% with an increase of 10% in 20 years' time. At the same time, 24% are exposed to drought, 10% to desertification, 19% to wildfires and only one installation is exposed to thawing permafrost; no changes to these values are expected within the next 20 years.

Regarding the *US Air Force*, most installations analysed, 89%, are exposed to wildfires and are expected to continue to be so in 20 years' time. However, this value is closely followed by floods, 56%, with a projected increase of 14%, and by drought, 56%, with a projected increase of 6%. Simultaneously, 11% of *US Air Force* installations are exposed to desertification and this value is expected to remain unchanged.

Overall, **flooding is already the primary climate-related natural hazard affecting US critical military installations** – 67%, irrespective of department (see Figure 13 rightmost panel) – and this is only expected to increase – by 9% – in 20 years. **Drought ranks second** as the climate-related natural hazard that most affects US critical military installations, specifically 54% of installations with a projected increase of 6%. Wildfires closely follow these values, with 46% of installations and a projected increase of 9%. Overall, of the 79 installations considered, only 8% are exposed to desertification and one to thawing permafrost.

A previous study (DOD, 2018) also concluded that flooding (in this case storm surge, but also river flooding and flooding due to heavy rainfall), was the main hazard affecting US military installations. However, strong winds ranked second, followed by extreme temperatures and wildfire. On the other hand, for ca. 50% of the 1684 sites analysed no implications were identified. Furthermore, airfield operations, transportation infrastructure, energy infrastructure, training/range facilities, and water/wastewater systems were reported as the top five assets most affected. Differences in values between the reports may be a result of several factors, such as the type and number of installations selected, or the understanding of climate-related natural hazards and their impacts, among others.

4.4.2 Missions and operations

Natural hazards and climate change may affect military capability and mission execution through direct or indirect effects from main or secondary hazards, or through the increase in demand for support activities, both domestically and internationally. Furthermore, increased uncertainty and adversity in the operating environment may hinder missions, for example by a lack of planned-for assets (CCS, 2016).

According to the DOD (2019a), missions can be hampered by more frequent and severe climate-related natural hazards that pose serious difficulties or through an increase in tensions, country instability and conflict escalation, which can also create pathways to hybrid threats. Examples of affected activities include:

- Intelligence, surveillance and reconnaissance;
- Contingency and mobility response;
- Combat and security;
- Personnel recovery and causality evacuation;
- Logistics and communications.

Simultaneously, as Artic ice melts due to global warming, accessibility (e.g., *North Sea Route*) and activities increase. This development is expected to demand more support from the military, such as search and rescue, and, consequently, longer and costlier acquisition and supply chains. The number of testing and training exercises in the Artic is also expected to increase.

The increase of demand for military support is also a consequence of recurring humanitarian assistance and disaster relief operations. The military provide capabilities (e.g., engineering, air traffic control, reconstruction) and assets, but also capacity building and training (e.g., global and public health, emergency management, baseline assessments), and are tasked to promote stability.

Finally, testing (i.e., the anticipated use of weapons, equipment, munitions, systems or components) and training in realistic and secure field conditions are critical for military proficiency and operational readiness. Natural hazards and climate change can result in over-planning, over-reliance in contingency plans, flawed situational awareness and decision-making, a higher chance of negative impacts (e.g., loss of life and injury, mission failure) and resources depletion. **Climate-related natural hazards may also lead to more maintenance, repair or replacement of infrastructure and equipment, health and safety risks** (e.g., extreme heat), ecosystem restoration efforts and to a forced reduction in the use of facilities (e. g., increase in no-fly days).

4.5 Overview of impacts

Natural hazards and climate change have the potential to negatively impact, directly or indirectly:

- Military installations and military assets;
- Military operations; and,
- Military strategy.

Negative impacts may affect military capability to different degrees, ranging from a nuisance to impacts that may actually defy the ability of the military to effectively fulfil their mission (e.g., GAO, 2014).

In Table 4, the general impacts of natural hazards and climate change on the military are listed and categorized as direct or indirect.

According to NATO ([12]), for air operations, warmer temperatures may degrade aircraft performance, overheat aircrafts and installations, resulting in higher energy consumption or the need for structural modifications. More sand and dust storms, due to desertification, will impair visibility, and changing wind creates difficulties in terms of take-off and landing at an airfield, but also during flight due to more wind shear and turbulence. In colder regions, de-icing requirements will need to be modified. In the case of maritime operations, those that take place in the Artic will be subject to higher winds and rough sea states, and more floating ice. In warmer regions, increased salinity can cause turbines to fail. Changing currents can affect Intelligence, surveillance and reconnaissance and submarine operations. Impacts inland can indirectly aggravate problems at sea through piracy (e.g., off the coast of Somalia) or migration (e.g., Mediterranean Sea). Land operations, may face more extreme environmental conditions (e.g., water scarcity, reduced visibility, heat stress, malfunctioning and wear and tear of equipment) and military logistics can be severely disrupted. Finally, a good number of operations, if not all, require reliable navigation and communication systems. Space weather can disrupt these and can cause personnel to be more exposed to radiation (e.g., in the Artic, during flights).

([12]) North Atlantic Treaty Organization (2021). NATO is responding to new challenges posed by climate change (accessed 1 July 2021). https://www.nato.int/docu/review/articles/2021/04/01/nato-is-responding-to-new-challenges-posed-by-climate-change/index.html

It is, therefore, crucial to reduce risk and bolster resilience to natural hazards and climate change so that the military may continue to effectively, but also efficiently, ensure EU security and defence. Military installations, defence critical infrastructure (cross-sector dependencies) and military assets are central to this process.

Table 4. General negative impacts, direct and indirect, of natural hazards and climate change on the military.

Direct impact	Loss of life, injury and wellbeing;
	Failure or structural damage, resulting in reduced integrity, safety and lifetime of military installations, military assets, and infrastructure (including critical on- and off-site lifelines such as energy, water, wastewater, communications and transportation);
	Change, environmental degradation or even loss (e.g., permanently inundated areas) of military land, including testing and training grounds.
Indirect impacts	Economic losses due to damage or loss of military installation and/or military assets, their replacement and repair, and claims against the military;
	Obstruction of roads and evacuation routes, resulting in closure, congestion, reduced speed, and in the disruption of on- and off-site transportation, supply chain and logistics;
	Entry restriction to military installations due to blocked access or safety concerns;
	Business interruption (e.g., intelligence, reconnaissance and surveillance, command and control, combat, testing and training, secure communications) and inability to meet operational requirements, affecting military readiness (e.g., impediment to fly) and sustainment (e.g., provision);
	Increased likelihood of mission disruption or failure due to additional uncertainty, altered environmental conditions, lack of or unsuitability (unfit for purpose) of military installations, military assets and supplies, and due to altered operational parameters, longer duration and higher costs;
	Higher costs due to an increase in maintenance and measures to reduce risk and build resilience, disaster response and recovery costs, but also costs due to remediation and restoration, closure, relocation, inoperability, delays and loss of attention;
	Increased likelihood of cascading effects, such as the triggering of Natech accidents (e.g., oil spills, fires and explosions);
	Increase in health and safety risks;
	Possible increase in socioeconomic vulnerability, insecurity and instability in the areas surrounding military installations or in a theatre of operations, and changes in geopolitical landscape and priorities.

Military installations exposed to different natural hazards may result in the change of plans and operations, business interruption such as testing and training, economic losses and strategic changes (NAVFAC, 2017). US Navy Installations, for example, were already experiencing negative impacts in 2017 (NAVFAC, 2017).

However, the impacts of natural hazards and climate change will likely be asymmetrical, because of the geographical location of each military installation – different locations are affected differently by natural hazards and climate change, but also due to their uniqueness in terms of facilities and master planning, cross-sector dependencies, their importance in terms of assets they house and operations they support, vulnerability of personnel, specific equipment and components, and resilience.

To enhance the protection and resilience of important infrastructures, the DOD established a Defence Critical Infrastructure Program (GAO, 2007) to address all hazards and threats to mission-critical installations and assets. It has used the concept of mission assurance as a way to integrate security, protection and risk management programmes (DOD Directive 3020.40), and defined defence critical infrastructure as all those military and civilian (i.e., owned and operated by local governments, foreign governments, private sector or cooperatives), domestic or foreign, on- and off-site facilities that are essential to project, support, and sustain military forces and operations (GAO, 2007). A crucial step, given that the DOD is "… one of the world's largest builders, owners, and operators of infrastructure and (…) land…" (DOD, 2020b).

5 Impacts of Climate-Related Natural Hazards – Case Studies

5.1 Extreme temperature

5.1.1 Extreme heat, Cyprus

Type of negative impact	Direct and indirect
Influencing factors	Heatwave, humidity, poor decision-making (land-use planning, risk underestimation. procedural failure)
Consequences	Death, injury, infrastructure and service collapse, business interruption, damage to property, economic loss, social, political and economic shock, cascading effect

According to the report by Polyviou (2011), 98 shipping containers, 83 of which containing artillery propellant and priming compounds, were apprehended in 2009 following a transport by ship in breach of *United Nations Security Council* (UNSC) *Resolution 1747*. The confiscated hazardous cargo, estimated at ca. $5x10^5$ kg of explosives (NATO MSIAC, 2012; Polyviou, 2011), was then stored in 81 containers and parcels and placed in an open space on top of a concrete slab at the *Cyprus Naval Base Evangelos Florakis* (Figure 14a).

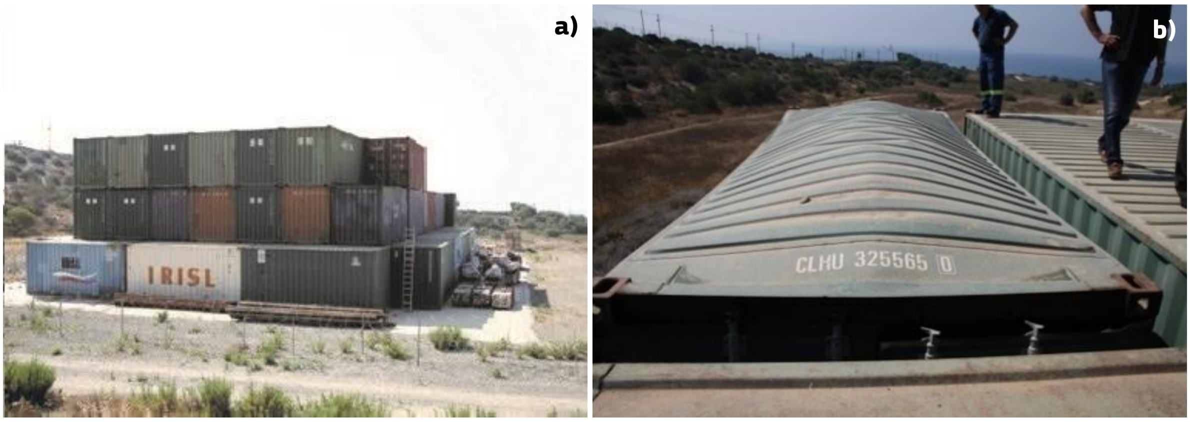

Figure 14. a) Stockpile of hazardous cargo at *Cyprus Naval Base Evangelos Florakis*; b) Deformed container of the same stockpile seven days before the explosion (NATO/MSIAC, 2012; Polyviou, 2011). Sources: NATO MSIAC

Nearly two years after, on 4 July 2011, the deformation (bulge) of a container was detected (Figure 14b). The most likely cause was the gradual destabilization of the stored artillery propellant due to temperature build-up, aided by high humidity and chemical reactions, which eventually lead to self-ignition, gas pressure increase within the container and explosion (Polyviou, 2011). On 11 July 2011, several containers self-ignited resulting in the sympathetic detonation of the stockpile with severe consequences (Figure 15).

The disaster resulted in the loss of 13 lives, 62 injuries, and extensive damage to surrounding infrastructure, including the *Vasilikos Power Station* (the largest of its time in Cyprus) that lead to cascading effects such as widespread power outages and rolling blackouts. It was the largest peacetime military accident ever recorded by NATO at that time, with an estimated cost of ca. €3 billion in damages (NATO MSIAC, 2012). This disaster also led to government spending cuts, public demonstrations and political repercussions.

The report by Polyviou (2011) concluded that human error was the main cause of this disaster, since the hazardous substances were not quickly disposed of and not properly stored (e.g., no shading, no venting, stockpiling of containers, obstruction of container doors and limited accessibility), allowing a prolonged exposure to weather conditions. A timely disposal of the hazardous substances, a distributed storage of smaller quantities, the disposition of containers to facilitate access, their protection from direct sunlight (e.g., warehouse), the use of cooling measures (e.g., venting) and a greater distance from critical infrastructure, such as the *Vasilikos Power Station*, would have reduced the risk of disaster.

Figure 15. Scene of the explosion at *Cyprus Naval Base Evangelos Florakis*. a) crater created by the explosion; b) damaged *Vasilikos Power Station*; c) damaged storage tank (NATO MSIAC, 2012; Polyviou, 2011). Source: NATO MSIAC

On the other hand, Cyprus was experiencing a meteorological dry period since 2010, which contributed to the development of extremely hot weather (Galvin et al., 2013). The *Cyprus Naval Base Evangelos Florakis* disaster perhaps would not have taken place if temperatures were cooler. In fact, other explosions of arms depots, such as those in the city of Baharka, Iraq, in 2018 and the cities of Baharka and Baghdad, Iraq, 2019, shared the same characteristic: high temperature during prolonged periods. As global average temperature rises and Artic sea ice and Eurasian snow cover decrease due to anthropogenic climate change, the likelihood of more frequent and stronger European heat waves increases (Christidis et al., 2015), which in turn will increase accident risks involving flammable and explosive substances.

Nicolae et al. (2016) also highlight additional causes for the accident such as sub-optimal decision-making and lack of firefighting plans. To these, it can also be added that the selection of the storage location, near a major energy infrastructure, was sub-optimal and that the application of the Seveso Directive (Directive 2012/18/E) by Cyprus to this case was limited due to its lack of scope for military installations (Polyviou, 2011).

Based on ARIA (2012b) and IAEA (2019), some possible measures to reduce risk and build resilience to extreme heat are listed in Table 5 and are categorized as structural, non-structural, and nature-based solutions (NBS).

Table 5. Examples of possible measures to reduce risk and build resilience to extreme heat.

Structural	Design and construct energy-efficient buildings (including high thermal insulation, thick walls, reflective surfaces, use of heat pumps for cooling, ground-coupled heat exchangers, natural ventilation, underground construction, reflective surfaces, minimize exposure to direct sunlight);
	Increase structural shading (e.g., for storage of hazardous materials), mechanical ventilation and air conditioning, and water cooling (e.g., water spray).
Non-structural	External shading (e.g., shutters), and reflecting window films and coating;
	Ensure power grid operation (load priority and shedding) and peak load capacity reserves (e.g., operating, frequency containment and restoration, replacement) and diversify power sources;
	Ensure sufficient water reserves for firefighting (e.g., heat-induced technological accidents);
	Ensure maintenance and renovation of infrastructure;
	Improved risk management (including cascading effects) beyond compliance, and early warning;
	Review and test contingency, emergency planning, guidelines, communication protocols and systems;
	Broad review of outage safety (e.g., critical infrastructure and military installations);
	Interruption and/or relocation of activities (e.g., testing and training);
	Partner with civilian entities in research, awareness raising, and capacity building;
Nature-Based Solutions	Increase shading using higher tree and vegetation density;
	Install green roofs and earth-covered facilities to reduce temperature fluctuations (e.g., earth-covered magazines and shelters).

The listed examples are in no particular order and there is no attempt to rank them.

5.1.2 Extreme cold, US

Type of negative impact	Direct and indirect
Influencing factors	Heavy rainfall, cold snap, snow and ice accumulation, wind, poor decision-making (risk underestimation)
Consequences	Death, infrastructure and service collapse, business interruption, economic loss, operational readiness, training and testing impaired

In January 2009, a major slow moving ice and snow storm that lasted four days, struck the US, particularly Kansas, Oklahoma, Arkansas, Missouri, Illinois, Indiana, Ohio, West Virginia, Tennessee, and Kentucky. During the storm, precipitation of 50 to 120 mm transitioned between snow, freezing rain and ice, causing surfaces to become ice coated (i.e., glaze) with a thickness of as much as 50 mm (Figure 16) (KPSC, 2009) ([13]). The ice and snow storm, considered as an anomalous event, was forecast one week in advance, giving authorities and utilities the time to take precautionary measures (KPSC, 2009) ([14]).

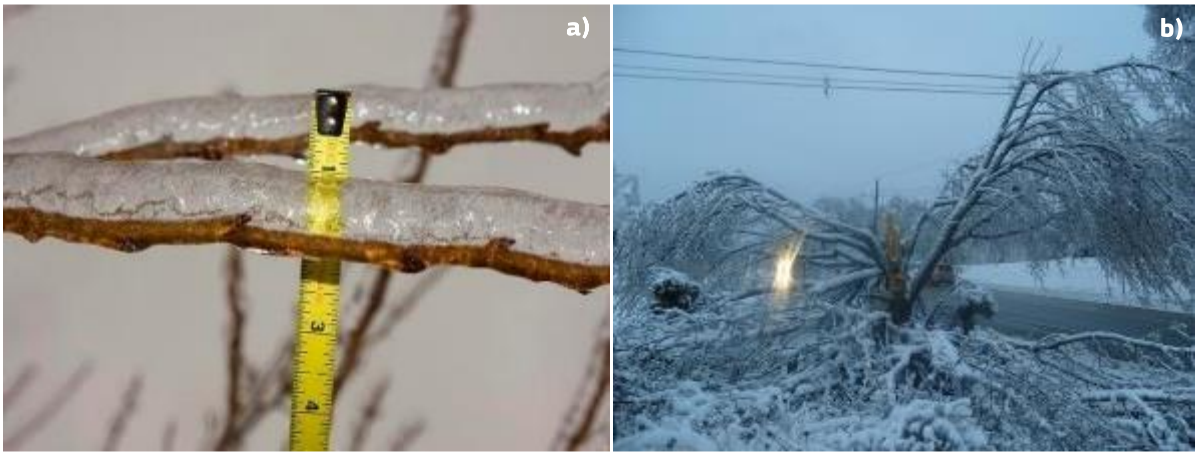

Figure 16. Effects of the ice and snow storm of January 2009 in Kentucky, US. a) Glaze thickness of more than 10 mm in a twig; b) Split tree possibly due to the weighing down of accumulated snow and ice ([8, 15]). Sources: a) Jessica Darnall/ *National Oceanic and Atmospheric Administration* (NOAA) *National Weather Service* (NWS); b) NOAA NWS

Mostly due to the extra weight of the ice, wind load, and falling trees and boughs on components of the electrical grid, widespread power outages took place in several areas. In Kentucky, the power outage was the largest ever reported at that time, with ca. 770,000 customer without electricity, light and heat, and in some cases for up to 10 days (KPSC, 2009) ([13, 15, 16]). In total, the storm toppled ca. 10,600 electricity poles, snapped bolts and buckled transmission towers (Figure 17) (KPSC, 2009).

(13) NOAA (2009). Ice and Snow Storm of January 26-28. National Weather Service (accessed 1 July 2021). https://www.weather.gov/lmk/jan_2009_ice_and_snow

(14) Spoden, P. J., Smith, R. R., Wielgos, C., Spaeth, D., Luecke, S., York, M. and Poole, B. (2010). Are You Really Prepared? A Real Life Assessment of WFO Paducah's Decision Support for the Ohio Valley Ice Storm 2009 (accessed 1 July 2021). https://www.weather.gov/media/meg/allhaz2010/spoden_WFO_PAH_ice_storm_all_hazardsworkshop.pdf

(15) Foster, S. Preliminary Impact Assessment from January 2009 Ice Storm. Midwestern Regional Climate Center (accessed 1 July 2021). https://mrcc.illinois.edu/cliwatch/0901/Ice%20Storm%202009-KY090131.pdf

(16) NOAA. Ice Storm 2009: Beauty and Destruction. National Weather Service (accessed 1 July 2021). https://www.weather.gov/media/pah/Top10Events/2009/Ice%20Storm%20Jan%2026-28%202009.pdf

Figure 17. Damaged transmission tower, electricity poles and power lines in Kentucky, US, during the ice and snow storm of January 2009 (KPSC, 2009). Source: Kentucky Public Service Commission

Exacerbated by the power outage, other infrastructure such as water and wastewater and communications faced disruption and damage (KPSC, 2009) ([13, 14, 15]). The negative impacts associated to the power outage led also to the propagation of multiple negative impacts such as water contamination and the impossibility to issue advisories about it due to the lack of communications (KPSC, 2009). The hazardous conditions (e.g., extreme cold, precipitation, wind, black ice, blocked roads, falling objects) and the negative impacts of the storm, as illustrated before, led to a shortage of fuel (e.g., gas and kerosene), batteries and generators, significantly impaired access to basic goods and the work of response teams (C2ES, 2018; KPSC, 2009) ([14, 15, 17]), and led to deployment of the entire Kentucky National Guard ([10, 17]). Overall, the storm resulted in a number of fatalities, some associated to hypothermia, but also carbon monoxide poisoning due to the use of backup power generators in unventilated places (Lutterloh et al., 2011) ([15, 17, 17]), and caused total economic losses of ca. US$616 million (KPSC, 2009).

The *US Army Fort Knox*, a military installation ca. 56 km south of Louisville, Kentucky, with ca. 440 km^2 and over 26,000 in population ([18]), was severely affected by the power outage, mostly due to its reliance on the civilian power grid ([19, 20, 21]). Although not much information can be found in the public domain, the negative impacts were strong enough to serve as a warning to the military. The storm led the *US Army* to undertake multiple energy initiatives in subsequent years to ensure energy security in the military installation, in case a severe power outage would happen again ([19, 21]).

In Table 6, some possible measures to reduce risk and build resilience to extreme cold are listed. The table is based on the studies of Karagiannis et al. (2019a) and ARIA (2012a).

(17) CBS News (2009). Kentucky Hardest Hit by Deadly Ice Storm (accessed 1 July 2021). https://www.cbsnews.com/news/kentucky-hardest-hit-by-deadly-ice-storm/

(18) Military OneSource. Fort Knox In-depth Overview (accessed 1 July 2021). https://installations.militaryonesource.mil/in-depth-overview/fort-knox

(19) Dyrdek, R. J. (2021). History, Status and Future Plans for the Energy Team at Fort Knox (accessed 1 July 2021). https://www.fedcenter.gov/Documents/index.cfm?id=36511&pge_prg_id=0&pge_id=1584

(20) Yale Climate Connection (2020). Fort Knox prepares for more extreme weather (accessed 1 July 2021). https://yaleclimateconnections.org/2020/05/fort-knox-prepares-for-more-extreme-weather/

(21) Ashley, P. (2018). Fort Knox goes 'off grid' with generator. WAVE 3 News (accessed 1 July 2021). https://www.wave3.com/2018/10/24/fort-knox-goes-off-grid-with-generator/

Table 6. Examples of possible measures to reduce risk and build resilience to extreme cold.

Structural	Design, construct and maintain roofs, or reroof, to withstand higher snow, rain-on-snow or ice loads (e.g., design load, geometry, steep pitch roofs, short-roof spans, smooth roof materials, uniform versus non-uniform load considerations, snow guards, insulation to control rapid snowmelt);
	Design, construct and maintain energy-efficient buildings (including thermal-efficiency, use of heat pumps, glazed obstructions, ground-coupled heat exchangers, heat accumulators, orientation to maximize exposure to direct sunlight);
	Structural orientation to minimize exposure to most likely wind directions and reduce snow accumulation;
	Improve corrosion resistance, including coating and inhibitors, of structures, lifelines and equipment;
	Integration of district heating and combined heat and power systems (cogeneration);
	Strengthen electrical power transmission and distribution systems to higher snow, ice and wind loads and low temperatures;
	Strengthen electrical power grids (e.g., implement redundancy, distributed generation) and use of micro-grids;
	Use of insulated buried heavy-walled welded steel or plastic pipes and conduits for lifelines (e.g., electric wiring, telecommunications) in non-frost-susceptible soils;
Non-structural	Trim trees surrounding structures;
	On-site backup power generation and storage, and transformer/battery/generator and spares reserve;
	Ensure power grid operation (load priority and shedding) and peak load capacity reserves (e.g., operating, frequency containment and restoration, replacement);
	Preventive draining and de-icing of sensitive equipment;
	Improved risk management (including compound events and cascading effects) beyond compliance, and early warning;
	Review and test contingency, emergency planning, guidelines, communication protocols and systems;
	Broad review of outage safety (e.g., critical infrastructure and military installations);
	Interruption and/or relocation of activities (e.g., testing and training);
	Partner with civilian entities in research, awareness raising, and capacity building.
Nature-Based Solutions	Green roofs and earth-covered facilities to reduce temperature fluctuations.

The listed examples are in no particular order and there is no attempt to rank them.

Box 6. A note on possible measures to reduce risk and build resilience to extreme cold

Since extreme cold may possibly involve floods due to rapid snowmelt or rain-over-snow events the possible measures to reduce risk and build resilience to floods also apply (e.g., Table 9)

5.2 Floods

5.2.1 Coastal floods, US

Type of negative impact	Direct
Influencing factors	Sea level rise, subsidence, high-tides, wind waves, storm surge
Consequences	Evacuation, business interruption, damage to property, economic loss, operational readiness, training and testing impaired

According to the NOAA data ([22]), on average, six to seven hurricanes have formed per year in the North Atlantic and, roughly, two of those have made landfall. With about 1 m of sea level rise (above the 2012 global mean sea level) due to global warming, 128 US military installations may be under threat, some of which are already experiencing the negative effects of coastal flooding (UCS, 2016a, b, c).

A numerical modelling exercise and analysis of 18 US coastal military installations (UCS, 2016b, c, d) found that, due to sea level rise and in the absence of any risk reduction measures, these installations are at risk of more frequent and extensive tidal and storm surge flooding (analysed separately) and of permanently inundated areas (Mean Higher High Water – average of the highest tidal height observed each day over a period of interest). Some could lose up to 30% of land by 2050, with ca. 1 m of sea level rise, up to 55% by 2070 and up to 75% by the end of the century (see Figure 18). These values are for an intermediate scenario of sea level rise, whereas for the highest scenario, with ca. 2 m of sea level rise, estimates are significantly higher by an additional 10 to 20%. Projected tidal and storm surge flooding for the years 2050, 2075 and 2100, were built based on the global sea level rise projections of Parris et al. (2012), and adjusted for local conditions using a correction factor.

In terms of frequency, some military installations could experience ca. 260 floods per year by 2050, for the intermediate scenario, ca. 480 floods per year by 2075, and by 2100 near constant flooding of flood-prone areas (i.e., flood susceptibility given the physical characteristics of the area). For the highest scenario the values increase roughly by 100 floods per year. Notably, a storm surge from a low-category storm on the Saffir-Simpson scale, is expected, by 2070 and 2100, to resemble a high-category storm of today.

The case of Norfolk, Virginia, is paradigmatic as it is home to one of the largest naval stations in the world and at the same time a hotspot for accelerated sea level rise (Sallenger Jr., et al. 2012; Strauss et al., 2016). The rate of sea-level rise in this region is almost twice the global average, partially because of its low-lying areas and ground subsidence, making it the second most exposed region to hurricanes in the US (Connolly, 2015; Ezer and Atkinson, 2014). From 1945 to 1985 there were 54 tropical cyclones that approached within ca. 333 km of Norfolk, Virginia, posing a threat to *US Naval Station Norfolk* (USNEPRF, 1982). Examples of historical events that affected the military installation include:

- August 1933, the Chesapeake–Potomac category 4 hurricane that produced ca. 1.6 m storm surge at Sewells Point, Norfolk, Virginia (Ezer and Atkinson, 2014);
- September 2003, category 5 Hurricane Isabel that produced ca. 1.6 m storm surge at Sewells Point, Norfolk, Virginia (Ezer and Atkinson, 2014), and may have flooded 6% of *US Naval Station Norfolk* (Li et al., 2013);
- November 2009, a category 2 “nor'easter” (non-tropical cyclone) that produced ca. 1.5 m storm surge at Sewells Point, Norfolk, Virginia (Ezer and Atkinson, 2014).

([22]) NOAA (2019). North Atlantic Hurricane Basin (1851-2018), Comparison of Original and Revised HURDAT (accessed 1 July 2021). https://www.aoml.noaa.gov/hrd/hurdat/comparison_table.html

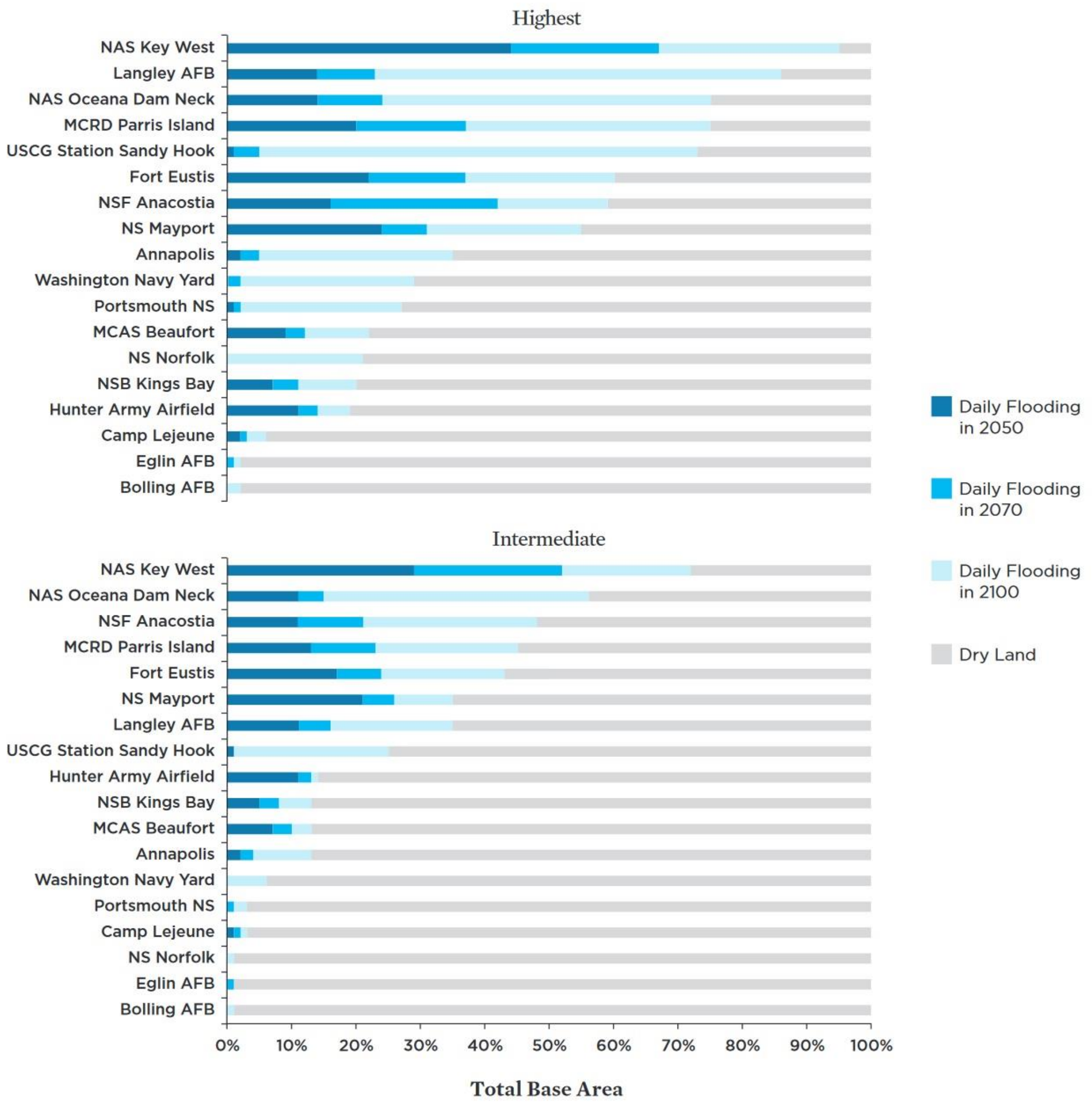

Figure 18. US coastal military installations projected to experience land loss, with ca. 1 and 2 m of sea level rise for the intermediate and high scenarios, respectively (UCS, 2016b). Source: UCS

US Naval Station Norfolk, on the eastern shore of Hampton Roads with an area of ca. 15 km^2, is already prepared for heavy weather, with remote hurricane anchorages to protect vessels (not for ocean-going ships that must sortie at the earliest opportunity), seawalls, bulkheads and floodgates, but also emergency plans and procedures. Much of the station is 3 m below mean sea level, of the few topographic rises most are only 12 m above mean sea level. Its location in a low-lying area, and of land subsidence, exposes the naval station even more to windstorms and floods by sea level rise and storm surge. Although relatively protected from wind waves, the military installation is exposed to the close passage of hurricanes, especially those moving northwards along the east coast, after Cape Henry (USNEPRF, 1982).

Flood modelling of *US Naval Station Norfolk* (UCS, 2016a) for the years 2050, 2070 and 2100, using two sea level rise scenarios (intermediate and highest), showed that tides are expected to cause more frequent floods, with larger extent and for longer duration (see Figure 19). In some cases, floods may span many high tide cycles. By 2100, in both sea level rise scenarios, flood-prone areas may be permanently underwater and roughly 20% of the naval station may flood regularly. On the other hand, category 1 storms that result in the flooding of 11% of the naval station with today's mean sea level, are expected to flood 19 to 27% by 2050, 35 to 66% by 2070 and 78 to ca. 100% by 2100, for the intermediate and highest sea level rise scenarios, respectively. Already today, 62% of the naval station is prone to flooding resulting from a category 2 storm; this may increase from 83 to 90% by 2050 and to ca. 100% from 2070 onwards. For baseline conditions, category 3 or 4 storms may commit the naval station to ca. 100% flooding already now; given this, sea level rise will result in an increase of flood depth.

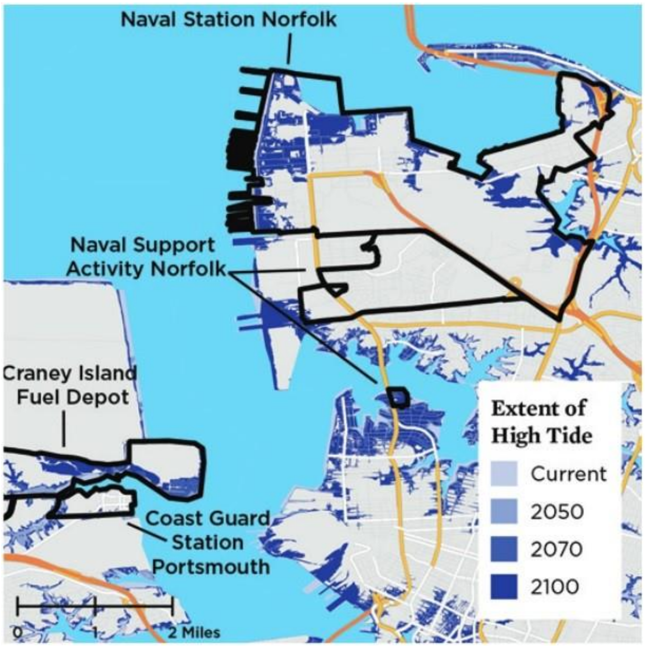

Figure 19. Baseline (current) and projected (2050, 2070 and 2100) extent of daily high tides for the highest sea level rise scenario (UCS, 2016a). Source: UCS

In terms of exposure of military facilities to sea level rise and storm surge, the following were identified (Connolly, 2015; Kramer, 2016; Mitchell, 2013; TPO, 2013):

- Facilities (including housing, warehouses, water and wastewater, data centres),
- Testing and training grounds, operational hubs, freight and equipment;
- Roads, bridges and parking;
- Waterways, piers and docks;
- Lifelines (e.g., water and wastewater, power grid, fuel pipelines, telecommunications and transportation);
- Utility services, logistics and supply chains.

Based on the studies of Cruz et al. (2009), Girgin and Krausmann (2015), Karagiannis et al. (2017, 2019a, b), Krausmann (2014), Krausmann and Mushtaq (2006), Krausmann et al. (2017), Necci et al. (2018, 2019) and Piccinelli and Krausmann (2013), some possible measures to reduce risk and build resilience to coastal floods are listed in Table 7. These measures were supplemented with information from Kramer (2016), USNEPRF (1982), Vuik et al. (2016) and the *United States Army Corps of Engineers* (USACE) ([23]).

([23]) USACE. Risk Management Strategies (accessed 1 July 2021). https://www.nad.usace.army.mil/CompStudy/Risk-Management-Strategies/

Table 7. Examples of possible measures to reduce risk and build resilience to coastal floods.

Structural	Design, construct, maintain, or reinforce flood defences (e.g., breakwaters, seawalls, bulkheads, revetments, storm surge barriers and gates, levees, berms, piers);
	Design, construct and maintain remote anchorages;
	Design, construct and maintain debris barriers (e.g., fences);
	Flood-proof existing structures (e.g., water-resistant materials, scour protection);
	Structural elevation (e.g., buildings, roads, rail tracks), with at least 1 m above base flood level for mission critical facilities;
	Rapid access to higher floors/roofs (e.g., flood shelters);
	Improve corrosion resistance, including coating and inhibitors of structures, lifelines and equipment;
	Improvement of drainage systems;
	Artificial aquifer recharge to slow subsidence and inhibit salt water intrusion;
	Land reclamation.
Non-structural	Deployable flood barriers and pump installation;
	Protection of safety critical systems or equipment from hydrostatic, hydrodynamic and wave loads or water ingress (e.g., waterproofing, appropriate design and placement);
	Relocation of equipment to higher ground, top floors and shelving;
	On-site backup power generation and storage, transformer/battery/generator/pump and spares reserve;
	Strengthening, anchoring and spill containment for piping and storage tanks (e.g., double shell, dikes, walls);
	Improved risk management (including compound events and cascading effects, high impact low probability, catastrophic and nuisance events) beyond compliance, monitoring (e.g., tide gauges, waver rider buoys) and early warning;
	Review and test contingency, emergency planning (including possible release of hazardous substances and occurrence of technological accidents), guidelines, communication protocols and systems;
	Targeted reassessment of safety margins (e.g., stress tests of power plants);
	Broad review of outage safety (e.g., critical infrastructure and military installations);
	Efficient pooling of resources across *EU Member States*;
	Restrictive land-use, managed retreat and land acquisition;
	Interruption and/or relocation of activities (e.g., testing and training, loading and unloading of hazardous materials that could result in their release);
	Relocation of aircrafts, ships, tactical- and non-tactical vehicles;
	Evacuation of personnel;
	Shutdown of lifelines (e.g., wastewater treatment), pipeline operations, purging of pipes and closing valves, de-inventorying of storage tanks of hazardous substances if possible and refill with water to prevent damage and accidents in case of floating;
	Efficient cleaning of drainage systems before an event, but also after to avoid mould;
	Partner with civilian entities in research, awareness raising, and capacity building.
Nature-Based Solutions	Restore coastal ecosystems to provide natural barriers, breakwaters and floodable waterfronts (e.g., marshes, mangroves, coral reefs; sand banks, sand dunes, barrier islands, overwash fans);
	Beach restoration (e.g., nourishment and stabilization, sand engines);
	Create retention basins;
	Slope stabilization (e.g., revegetation).

The listed examples are in no particular order and there is no attempt to rank them.

5.2.2 River floods, US

Type of negative impact	Direct
Influencing factors	High soil moisture and frozen soils, heavy snowfall and rain, rapid snowmelt, ice jams, topography, river morphology, poor decision-making (land-use planning)
Consequences	Death, damage to infrastructure and service disruption, evacuation, business interruption, damage to property, economic loss, operational readiness, training and testing impaired

After a warm and wet 2018/19 winter, which saturated the soils (high soil moisture), low temperatures and record-breaking snowfall hit Nebraska and by March 2019 the region was characterized by a thick and moist snowpack (up to 0.1 m snow water equivalent – indication of the amount of water should the snow melt), and deep frozen ground and rivers (e.g., the Platte river had a ca. 0.4 m ice depth at Leshara, Nebraska) (Flanagan et al., 2020) ([24]).

These conditions set the stage for what followed over the particularly flat terrain of the Great Plains. A bomb Cyclone developed over southern Colorado ([25]), moved towards the east and produced heavy rain over Nebraska. The rain over snow caused its rapid melting, and in combination with antecedent conditions of frozen and saturated soils, which prohibited infiltration, the runoff quickly overwhelmed the rivers that were already flowing at above-average since 2018. This led to a record-breaking flood (Flanagan et al., 2020), that in many cases was exacerbated by ice impeding the normal flow of water, particularly in river meanders and bridges.

The 2019 Missouri River and North Central Flooding, as it is known, caused three people to lose their lives, and forced several others to be evacuated ([26]). It also resulted in very high loss and damage in the region, from homes, to transport (e.g., roads, bridges) ([26]) and water infrastructure ([27]), levees and dams ([26]), the threatening of a nuclear power plant ([26]), the disruption of fuel supply ([28]), agricultural fields ([27]) and two military installations, impairing operational readiness and training. According to NOAA ([29]), this inland flood was one of the costliest events on record (estimated at ca. US$10 billion).

The *US Offutt Air Force Base*, sitting at the confluence between the Missouri and Platte rivers, was one of the military installations that was severely affected by the floods. Figure 20 shows the record-breaking water levels observed at a gauge station immediately south of the Missouri and Platte rivers confluence.

Figure 21 and Figure 22, show a comparison of satellite images of the region of Omaha, Nebraska, where the *US Offutt Air Force Base* is located, with the rivers below or at bankfull conditions and the conditions corresponding to the flood.

([24]) NOAA. National Weather Service, 2019 Spring Flood and Water Resource Outlook (accessed 1 July 2021). https://www.weather.gov/dvn/2019_springfloodoutlook

([25]) NOAA (2019). #3 Bomb Cyclone March 13. National Weather Service (accessed 1 July 2021). https://www.weather.gov/bou/BombCycloneMarch13th2019

([26]) NASA (2019). Midwest Flooding March 2019 (accessed 1 July 2021). https://appliedsciences.nasa.gov/what-we-do/disasters/disasters-activations/midwest-flooding-march-2019

([27]) Cusick, D. (2019). No End in Sight for Record Midwest Flood Crisis. Scientific American (accessed 1 July 2021). https://www.scientificamerican.com/article/no-end-in-sight-for-record-midwest-flood-crisis/

([28]) Kumar, D. K. and Kelly, S. (2019). UPDATE 3-Midwest flooding disrupts U.S. crude, fuel cash markets. Reuters (accessed 1 July 2021). https://www.reuters.com/article/usa-crude-cushing-idUSL2N2340W6

([29]) NOAA (2021). National Centers for Environmental Information, US Billion-Dollar Weather and Climate Disasters (accessed 1 July 2021). https://www.ncdc.noaa.gov/billions/

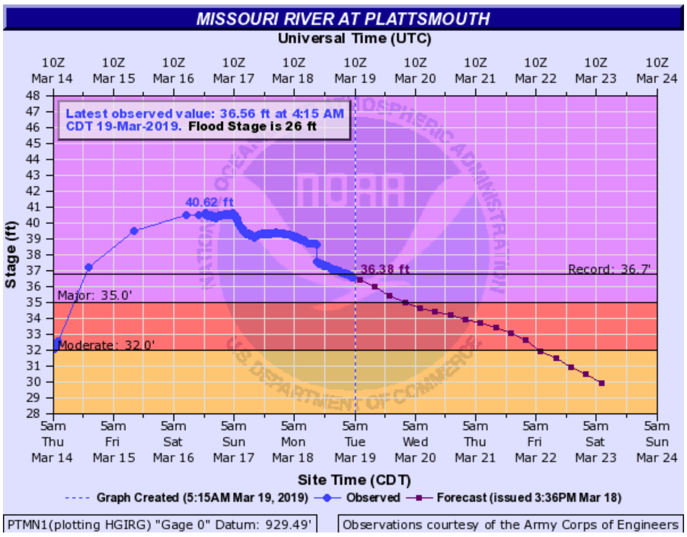

Figure 20. Spring flooding summary 2019 for Plattsmouth, location immediately downstream from the Platte and Missouri River confluence, south of *US Offutt Air Force Base*. The plot shows a record-breaking water level, observed on the 16 March 2019, of ca. 12 m. Source: NOAA NWS

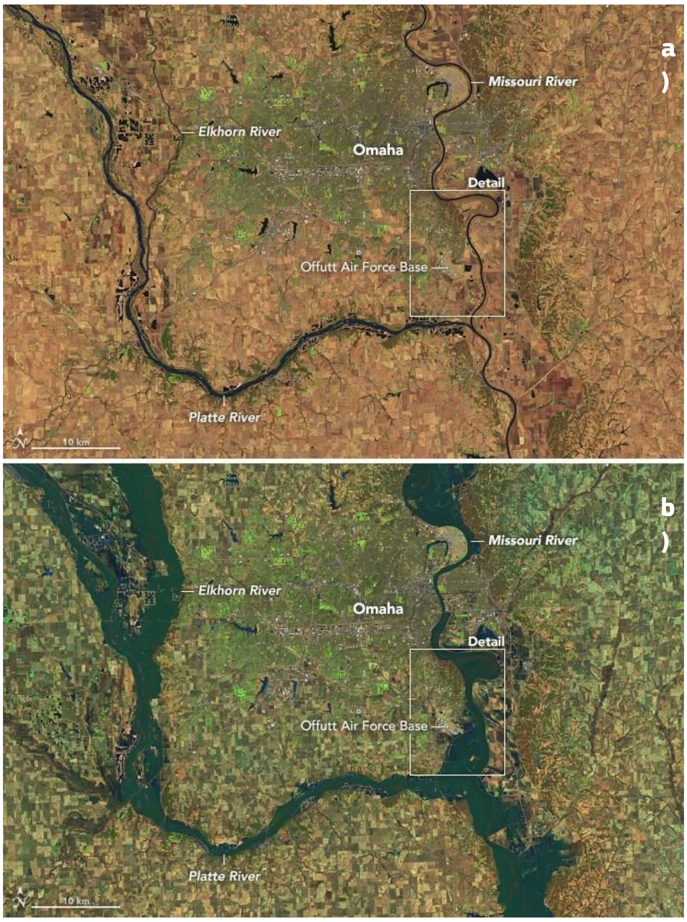

Figure 21. False-colour images, obtained from the Landsat 8 satellite, showing the Platte and Missouri River confluence where the *US Offutt Air Force Base* is located, south of the city of Omaha, Nebraska, Midwest US, a) on 20 March 2018, below or at bankfull conditions, and b) on 16 March 2019, during the flood. Source: Joshua Stevens/*National Aeronautics and Space Administration* (NASA) *Earth Observatory* (EO)

Figure 22. Zoom in of false-colour images, obtained from the Landsat 8 satellite, showing the Platte River, Papillion Creek and the *US Offutt Air Force Base*, Nebraska, Midwest US, a) on 20 March 2018, below or at bankfull conditions, and b) on 16 March 2019, during the flood. Source: Joshua Stevens/NASA EO

The *US Offutt Air Force Bas*e housed, among others, the *US Strategic Command*, which oversees US nuclear forces, and the largest wing (55th) within the *US Air Combat Command*, charged with space, information, missile defence, global command and control, intelligence, surveillance, and reconnaissance, global strike and deterrence (the US nuclear arsenal), and combating weapons of mass destruction.

The military quickly evacuated the base, mobilised to save equipment, munitions and aircraft (moved to higher ground or flown off-site) and put in place more than 235,000 sandbags and 460 flood barriers to help prevent flooding ([30]). Nevertheless, the floodwaters overwhelmed the south eastern side of the military installation. A significant portion of the runway was underwater, which led to its closing, 60 buildings were damaged, some with more than 2 m of water inside ([31]), equipment such as training simulators ([32]), electrical ([33]) and water pump stations ([32]) were damaged, and personnel had to be evacuated and reduced to essential ([34]). High security facilities and intelligence data and analyses were put under round-the-clock security because of non-functioning security systems. A good number of material was lost with unknown consequences to national security. Recovery costs were estimated at ca. US$650 million ([35]).

The second military installation affected by the 2019 Missouri River and North Central Flooding, was *US Camp Ashland*, ca. 40 km west of *US Offutt Air Force Base*, that conducts training of up to 100,000 military personnel each year ([36]). The installation was completely flooded, 51 of 62 buildings were damaged and training had to be moved ([36]). Recovery costs were estimated at ca. US$62 million ([37]).

([30]) 55th Wing Public Affairs (2019). Team Offutt battling flood waters. Offutt Air Force Base (accessed 1 July 2021). https://www.offutt.af.mil/News/Article/1787242/team-offutt-battling-flood-waters/

([31]) Brackett, R. (2019). Nebraska's Offutt Air Force Base Inundated by Floodwaters; Runway Closed; 60 Buildings Damaged. The Weather Channel (accessed 1 July 2021). https://weather.com/news/news/2019-03-17-offutt-air-force-base-inundated-by-flood-waters

([32]) Cohen, R. S. (2019). Water, Water Everywhere. Air Force Magazine (accessed 1 July 2021). https://www.airforcemag.com/water-water-everywhere/

([33]) Cunningham, L. (2019). Power crews prevent electrical catastrophe, 55th Wing Public Affairs. Offutt Air Force Base (accessed 1 July 2021). https://www.offutt.af.mil/News/Article/1800099/power-crews-prevent-electrical-catastrophe/

([34]) Losey, S. (2019). Floodwaters overwhelm one-third of Offutt; nine aircraft evacuated. Air Force Times (accessed 1 July 2021). https://www.airforcetimes.com/news/your-air-force/2019/03/18/floodwaters-overwhelm-one-third-of-offutt-nine-aircraft-evacuated/

([35]) Losey, S. (2019). After massive flood, Offutt looks to build a better base. Air Force Times (accessed 1 July 2021). https://www.airforcetimes.com/news/your-air-force/2020/08/07/after-massive-floods-offutt-looks-to-build-a-better-base/

([36]) Associated Press (2019). Nebraska National Guard camp recovering after flooding (accessed 1 July 2021). https://apnews.com/article/f30acbef64194d86956c309e43c3470a

([37]) Associated Press (2019). Nebraska National Guard pursues $62M plan to rebuild camp (accessed 1 July 2021). https://apnews.com/article/3a6b3b52dba444b7aa0066e9250c37b6

In Figure 23. Aerial photos of the US Midwest Floods of March 2019 at a) US Offutt Air Force Base and b) US Camp Ashland. Sources: a) Tech. Sgt. Rachelle Blake/DOD and b) Maj. Gen. Daryl Bohac/DOD an aerial view of the two military installations is given to illustrate the dimension of the disaster.

Figure 23. Aerial photos of the US Midwest Floods of March 2019 at a) US Offutt Air Force Base and b) US Camp Ashland. Sources: a) Tech. Sgt. Rachelle Blake/DOD and b) Maj. Gen. Daryl Bohac/DOD

In Table 8 some possible measures to reduce risk and build resilience to river floods are listed. The table is based on the studies of Girgin and Krausmann (2015), Karagiannis et al. (2017, 2019a, b), Krausmann (2014), Krausmann and Mushtaq (2006), Krausmann et al. (2017), Necci et al. (2018, 2019), Piccinelli and Krausmann (2013) and Sepheri et al. (2019).

Table 8. Examples of possible measures to reduce risk and build resilience to river floods.

Structural	Design, construct, maintain, or reinforce flood defences (e.g., weirs, levees, guide bunds, flood walls, barriers and gates, diversion channels);
	River engineering (e.g., deepening, widening, straightening, reinforcing bed and banks, dredging);
	Design, construct and maintain diversion channels, dams and reservoirs, debris barriers (e.g., fences);
	Flood-proof existing structures (e.g., appropriate building materials, scour protection);
	Structural elevation (e.g., buildings, roads, rail tracks), with at least 1 m above base flood level for mission critical facilities;
	Rapid access to higher floors/roofs (e.g., flood shelters);
	Improve corrosion resistance, including coating and inhibitors of structures, lifelines and equipment;
	Improvement of drainage systems.
Non-structural	Deployable flood barriers and pump installation;
	Protection of safety critical systems or equipment from hydrostatic, hydrodynamic and wave loads or water ingress (e.g., waterproofing, appropriate design and placement);
	Relocation of equipment to higher ground, top floors and shelving;
	On-site backup power generation and storage, transformer/battery/generator/pump and spares reserve;
	Strengthening, anchoring and spill containment measures for piping and storage tanks (e.g., double shell, dikes, walls);
	Improved risk management (including compound events and cascading effects, high impact low probability, catastrophic and nuisance events) beyond compliance, monitoring (e.g., stream gauges) and early warning;
	Review and test contingency, emergency planning (including possible release of hazardous substances and occurrence of technological accidents), guidelines, communication protocols and systems;
	Targeted reassessment of safety margins (e.g., stress tests of power plants);
	Broad review of outage safety (e.g., critical infrastructure and military installations);
	Efficient pooling of resources across *EU Member States*;
	Restrictive land-use, managed retreat and land acquisition;
	Interruption and/or relocation of activities (e.g., testing and training, loading and unloading of hazardous materials that could result in their release);
	Relocation of aircrafts, tactical- and non-tactical vehicles;
	Evacuation of personnel;
	Shutdown of lifelines (e.g., wastewater treatment), pipeline operations, purging of pipes and closing valves, de-inventorying of storage tanks of hazardous substances if possible and refill with water to prevent damage and accidents in case of floating;
	Efficient cleaning of drainage systems before an event, but also after to avoid mould;
	Partner with civilian entities in research, awareness raising, and capacity building.
Nature-Based Solutions	Restore floodplains, river bed and river banks, and wetlands;
	River re-meandering;
	Setting back levees (e.g., room for the river project in Nijmegen, The Netherlands);
	Design and construct flood bypass and polders, live check dams;
	Create retention basins;
	Slope stabilization (e.g., revegetation);
	Headwater afforestation or reforestation.

The listed examples are in no particular order and there is no attempt to rank them.

5.2.3 Flash flood, Egypt

Type of negative impact	Direct
Influencing factors	Topography, dry climate, poor decision-making (land-use planning, procedural failure)
Consequences	Death, injury, evacuation, damage to property, economic loss, social, political and economic shock, , environmental pollution

The Asyut region in Egypt is an arid region with little vegetation. Rainfall in this region is irregular and rainstorms are rare but intense. At the foot slope of the limestone Asyut plateau drainage basin, in the west bank of the river Nile and 320 km south of Cairo, there is Dronka (also known as Durunka) village. The Wadi Asyut – Arabic term for a dry valley – is characterized by different elevations and ridges. All these characteristics, in the case of heavy rainfall, help the rapid flow of water towards the village with very little water volume being lost along the valley (Ezz, 2018).

In 1994, immediately at the outlet of the Wadi Asyut there was a military fuel complex (Abulnour, 2014) ([38]), which stored ca. 40,000 tons of strategic military fuel ([40]), and a railroad track that traversed the outlet over a bridge. These facilities were located just some hundreds of meters from the nearest house.

On 1 November 1994, a cloud system of ca. 300 to 500 km horizontal scale crossed Egypt towards the east, resulting in severe thunderstorms and rainfall. The observed rainfall was of more than 20 mm in one day, which is extreme considering that Cairo receives that amount in one year. On 2 November 1994, the synoptic situation did not improve over Egypt, with winds reaching ca. 20 m/s, in comparison with less than 10 m/s the previous day. A sharp line of clouds, typically associated with thunderstorms, was identified over the country that same day using satellite images (Krichak et al., 2000), and Dronka village was swept by a flash flood causing a tragedy ([39]).

According to Ezz (2018) the flash flood corresponded to a 100-year return period event. Three storage tanks at a military fuel depot, with ca. 5000 tons of jet or diesel fuel each, ignited following a lightning strike (Cerveny et al., 2017). The blazing fuel was swept away in the floodwaters causing a large fire in the village, killing 475 people ([40]), injuring hundreds of others (e.g., multiple burns) and destroying hundreds of houses leaving several people homeless. This event was classified by the World Meteorological Organization as the one with the highest mortality indirectly associated to lightning (Cerveny et al., 2017; Gabr and Bastawesy, 2015) as explained by the synoptic situation. However, some newspapers reported that the cause of fire ignition, and possibly explosion, was a short circuit ([40]).

On 3 November 1994 the fire was still burning and floodwaters did not recede, which in addition to debris blocking roads, hampered response and search and rescue. There were fears that this could become an opportunity for fundamentalists to broaden their base of support, like after the 1992 earthquake in Cairo.

The government acknowledged that they had not responded to the request made by local authorities before the accident to relocate the fuel depot. At the same time, the relatively small size of the drainage basin and the prevalence of dry climate created a lack of flood risk perception and management (Abdel-Fattah et al., 2017).

In Table 9 some possible measures to reduce risk and build resilience to flash floods are listed. The table is based on the studies of Girgin and Krausmann (2015), Karagiannis et al. (2017, 2019a, b), Krausmann (2014), Krausmann and Mushtaq (2006), Krausmann et al. (2017), Necci et al. (2018, 2019) and Piccinelli and Krausmann (2013). It should be noted that some of the listed measures depend on the existence of an efficient forecast and early warning system for rainfall-induced flash floods. However, these systems are still at an initial stage of development (Rözer et al., 2021).

([38]) Associated Press (1994). Egypt - Storm And Fire Causes Many Casualties (accessed 1 July 2021). http://www.aparchive.com/metadata/Egypt-Storm-And-Fire-Causes-Many-Casualties/6f9e9a5409d86310b32cb649860ac794?query=Floods+egypt&current=1&orderBy=Relevance&hits=22&referrer=search&search=%2fsearch%2ffilter%3fquery%3dFloods%2520egypt%26from%3d1%26orderBy%3dRelevance%26allFilters%3d1990%253ADecade%26ptype%3dIncludedProducts%26_%3d1623057129734&allFilters=1990%3aDecade&productType=IncludedProducts&page=1&b=0ac794

([39]) United Nations Office for the Coordination of Humanitarian Affairs (1994). Egypt - Floods Nov 1994 UN DHA Situation Reports 1-4 (accessed 1 July 2021). https://reliefweb.int/report/egypt/egypt-floods-nov-1994-un-dha-situation-reports-1-4

([40]) Martone, J. (1994). Angry Townspeople Survey Devastation; Death Toll Over 475. Associated Press (accessed 1 July 2021). https://apnews.com/article/ba0faa75aa24b96fb4a6d0d1da21c6c0

Table 9. Examples of possible measures to reduce risk and build resilience to flash floods.

Structural	Flood-proof existing structures (e.g., appropriate building materials, scour protection);
	Structural elevation (e.g., buildings, roads, rail tracks), with at least 1 m above base flood level for mission critical facilities;
	Rapid access to higher floors/roofs (e.g., flood shelters);
	Improve corrosion resistance, including coating and inhibitors of structures, lifelines and equipment;
	Improvement of drainage systems.
Non-structural	Deployable flood barriers and pump installation;
	Protection of safety critical systems or equipment from hydrostatic, hydrodynamic and wave loads or water ingress (e.g., waterproofing, appropriate design and placement);
	Relocation of equipment to higher ground, top floors and shelving;
	On-site backup power generation and storage, transformer/battery/generator/pump and spares reserve;
	Strengthening, anchoring and spill containment for piping and storage tanks (e.g., double shell);
	Improved risk management (including compound events and cascading effects, high impact low probability, catastrophic and nuisance events) beyond compliance and early warning;
	Review and test contingency, emergency planning (including possible release of hazardous substances and occurrence of technological accidents), guidelines, communication protocols and systems;
	Broad review of outage safety (e.g., critical infrastructure and military installations);
	Efficient pooling of resources across *EU Member States*;
	Restrictive land-use, managed retreat and land acquisition;
	Interruption and/or relocation of activities (e.g., testing and training, loading and unloading of hazardous materials that could result in their release);
	Relocation of aircrafts, tactical- and non-tactical vehicles;
	Evacuation of personnel;
	Shutdown of lifelines (e.g., wastewater treatment), pipeline operations, purging of pipes and closing valves, de-inventorying of storage tanks of hazardous substances if possible and refill with water to prevent damage and accidents in case of floating;
	Efficient cleaning of drainage systems before an event, but also after to avoid mould;
	Partner with civilian entities in research, awareness raising, and capacity building.
Nature-Based Solutions	Create retention basins, enhance infiltration (e.g., reduce impervious surfaces, increase green spaces, green roofs, urban water buffers) and drainage.

The listed examples are in no particular order and there is no attempt to rank them.

5.3 Drought, US

Type of negative impact	Indirect
Influencing factors	Rapid population growth, high water demand, poor decision-making (water management)
Consequences	Business interruption, training and testing impaired

Water is not always available locally when needed, at good quality and cost. The DOD uses billions of litres of water to operate. According to GAO (2019), 102 military installations may face water scarcity, and may not have sufficient water to meet demand for uses such as drinking, sanitation, training, weapons testing, rocket launches, cooling, noise and vibration suppression, firefighting and fire suppression.

This situation will likely worsen as global warming continues (NAVFAC, 2018). It is clear that water scarcity needs to be seen in the perspective of competing demands (e.g., human consumption, irrigation, thermal power generation) and rapid population growth, be it within a military installation (e.g., additional air squadrons at the US Marine Corps Air Station Yuma, Arizona), or be it in the surrounding communities.

Some military installations, such as the US Marine Corps Base Camp Pendleton in California, US, which accommodates a wide variety of open-air training ranges, are already experiencing this reality. The US Marine Corps Base Camp Pendleton has been pumping wastewater into the aquifer to counteract its depletion for a number of years ([41]). However, due to severe drought in California, they have faced the need to find new solutions to conserve water (e.g., water restricting devices), but also alternative supply sources to meet demand (e.g., desalination). A major concern in this military installation relates to Lake O'Neil, the main backup supply and recreation centre, which loses large quantities of water every year and relies on rainfall and runoff (including snowmelt) for replenishment. The military installation has also been involved in long court disputes over water rights over the years (e.g., Santa Margarita River; Cooke, 1956).

Other examples include US Mountain Home Air Force Base, Idaho, where water use had to be drastically reduced in 2017 and 2018 because supply could not meet demand.

Based on IAEA (2019) some possible measures to reduce risk and build resilience to drought are listed in Table 10.

([41]) Aro, A. (2009). Camp Pendleton leads the way with Recycled Water Program. Marines: The official website of the United States Marine Corps (accessed 1 July 2021). https://www.pendleton.marines.mil/News/News-Article-Display/Article/536836/camp-pendleton-leads-the-way-with-recycled-water-program/

Table 10. Examples of possible measures to reduce risk and build resilience to drought.

Structural	Design and construct dams, reservoirs, aqueducts, canals and wells;
	Artificial aquifer recharge (e.g., carry-over storage) and water desalination;
	Improve water and wastewater treatment and reuse, irrigation and water supply systems.
Non-structural	Ensure power grid operation (load priority and shedding) and peak load capacity reserves (e.g., operating, frequency containment and restoration, replacement) and diversify power sources;
	Ensure sufficient water reserves for firefighting (e.g., heat-induced technological accidents);
	Ensure maintenance and renovation of infrastructure;
	Increase water efficiency, water transfers, conjunctive use, and distribution by tankers and trucks;
	Introduce restriction on water use and rationing;
	Improved risk management (including compound events and cascading effects) beyond compliance, monitoring, forecast and early warning;
	Review and test contingency, emergency planning, guidelines, communication protocols and systems;
	Relocation of activities (e.g., testing and training);
	Partner with civilian entities in research, awareness raising, and capacity building;
Nature-Based Solutions	Restore ecosystems (e.g., wetlands, grasslands, forests);
	Enhance infiltration (e.g., reduce impervious surfaces, increase green spaces, green roofs, urban water buffers, infiltration basins, terracing, percolation ponds);
	Small scale rainwater harvesting;
	Design and construct live check dams and windbreaks;
	Ecosystem management (e.g., controlled grazing).

The listed examples are in no particular order and there is no attempt to rank them.

5.4 Windstorm, US

Type of negative impact	Direct and indirect
Influencing factors	Poor decision-making (land-use planning)
Consequences	Death, injury, evacuation, infrastructure and service collapse, business interruption, damage to property, economic loss, operational readiness, training and testing impaired

In August 1992, after hitting the Bahamas, Hurricane Andrew, a category 5 hurricane on the Saffir-Simpson scale (Landsea et al., 2004), made landfall near Homestead, Florida, creating a path of destruction ca. 35 km wide, before reaching Louisiana weakened (see Figure 24). Hurricane Andrew was the second strongest hurricane to make landfall in Florida since the Labour Day Hurricane, 1935.

At Fender point, 13 km east-northeast of Homestead, Hurricane Andrew was estimated to have had a central pressure of 922 mbar (Mayfield et al., 1994), a maximum 1-min surface wind of ca. 75 m/s and wind gusts between 82 and 87 m/s (Landsea et al., 2004). Although Hurricane Andrew produced in Florida ca. 5 m storm tide (i.e., sum of the storm surge and tide) and rainfall between 50 and 200 mm (Mayfield et al., 1994), almost all of the damage in Florida was caused by strong winds (Rappaport, 1994).

Hurricane Andrew resulted in 65 fatalities, an estimated damage of ca. US$25 billion, being one of the costliest hurricanes to make landfall in the US. It destroyed ca. 25,000 homes and damaged ca. 100,000 others, leaving 250,000 people in temporary homelessness (Rappaport, 1994) ([42]). According to USACE ([43]), Hurricane Andrew destroyed schools, disrupted the provision of basic services such as energy, water supply, wastewater treatment, communications and transportation (e.g., debris blocked roads).

Figure 24. Time-lapse view of Hurricane Andrew moving from East to West on August 23, 24 and 25, 1992. Imagery obtained from the Geostationary Operational Environmental Satellite (GOES-7). Source: Rob Gutro/NASA *Goddard Space Flight Center*

At *US Air Force Base Homestead*, most personnel and aircrafts were evacuated before hurricane landfall. According to the *US Environmental Protection Agency* (EPA) ([44]), the Air Force Base, which occupied an area of ca. 12 km^2, saw 97% of its facilities and military assets severely damaged or rendered unusable, such that it entered the process of “base realignment and closure” in 1993. The next year, the military installation was considered in excess and was effectively closed, except for a portion that transitioned to what is now the *US Air Reserve Base Homestead*. The devastation caused by Hurricane Andrew becomes evident just by looking at the photos of the aftermath (Figure 25).

More recently, on 12 September 2018, *US Camp Lejeune*, a Marine Corps military installation located in North Carolina, was hit by category 4 Hurricane Florence with a 1-minute sustained wind speed of ca. 67 m/s

([42]) Rappaport, E. Preliminary Report Hurricane Andrew 16 - 28 August, 1992 (accessed 1 July 2021). https://www.nhc.noaa.gov/1992andrew.html

([43]) USACE (2002). Historical Vignette 055 - The Corps came to the Aid of Florida in the Aftermath of Hurricane Andrew (accessed 1 July 2021). https://www.usace.army.mil/About/History/Historical-Vignettes/Relief-and-Recovery/055-Hurricane-Andrew/

([44]) EPA. Homestead Air Force Base, FL, Cleanup Activities (accessed 1 July 2021). https://cumulis.epa.gov/supercpad/SiteProfiles/index.cfm?fuseaction=second.cleanup&id=0404746

(Stewart and Berg, 2019). The hurricane damaged the roofs on the base allowing for rainfall to accumulate inside the buildings ([45]), also widespread outages were felt ([46]). Damage to the military installation was estimated at ca. US$3.6 billion ([47]). Hurricane Florence also negatively impacted several other US military installations located in different states ([47]): in North Carolina, the *US Fort Bragg*, *US Marine Corps Air Station New River*, *US Marine Corps Air Station Cherry Point*, *US North Carolina National Guard*, in South Carolina, the *US Marine Corps Recruit Depot Parris Island*, *US Charleston Air Force Base*, *US Shaw Air Force Base*, *US Army Fort Jackson*, and in Virginia the *US Army Garrison Fort A. P. Hill*, *US Joint Base Langley-Eustis* and *US Naval Station Norfolk*.

Figure 25. Severe damage caused by Hurricane Andrew in 1992 within *US Air Force Base Homestead* and its vicinity. a) An aerial view of the devastation in Homestead; b) Damaged *Armed Forces Recruiting Center*; c) Damaged control tower; d) A destroyed pair of F-16 Fighting Falcons and hangar. Sources: a) Sgt. 1st Class Javier Otero/DOD; b) PH2 Davis Tucker/DOD; c) Master Sgt. James Ferguson/DOD; d) Master Sgt. Don Wetterman/DOD

On 10 October 2018, category 5 Hurricane Michael swept over Florida with a wind speed of ca. 70 m/s (Beven II et al., 2019). As a result 79 people lost their lives, 22,000 people were left homeless, and every house in the hurricane's path was destroyed ([48]). Electricity and water supply were disrupted ([49]). The *US Tyndall Air Force Base* was forced to evacuate non-essential personnel and was severely damaged, with 484 buildings destroyed and the other in need of repair ([50]). Besides buildings, several F-22 aircrafts were damaged ([51]). The cost of Hurricane Michael was estimated at US$25 billion, of which ca. US$5 billion is associated to *US Tyndall Air Force Base* ([52]).

([45]) Price, J. (2019). Hurricane Florence Repairs At Camp Lejeune Will Cost Billions, And More Big Storms Are Likely. WUSF public media (accessed 1 July 2021). https://wusfnews.wusf.usf.edu/2019-01-16/hurricane-florence-repairs-at-camp-lejeune-will-cost-billions-and-more-big-storms-are-likely

([46]) Thayer, R. and Dickstein, C. (2018). How Florence is affecting area bases. Stars and Stripes (accessed 1 July 2021). https://www.stripes.com/how-florence-is-affecting-area-bases-1.547531

([47]) Snow, S. (2018). $3.6 billion price tag to rebuild Lejeune buildings damaged by Hurricane Florence. Marine Corps Times (accessed 1 July 2021). https://www.marinecorpstimes.com/news/your-marine-corps/2018/12/12/36-billion-price-tag-to-rebuild-lejeune-buildings-damaged-by-hurricane-florence/

([48]) Schneider, M. (2019). A year after Michael, Florida community still in crisis. Associated Press (accessed 1 July 2021). https://apnews.com/article/us-news-ap-top-news-hurricane-michael-hurricanes-mental-health-0d260a9ec44545458ab1f25b6f969a5a

([49]) Beehler, A. and Surash, J. E. J. (2020). Cutting the Cord to Test Energy Resilience. US Army (accessed 1 July 2021). https://www.army.mil/article/234514/cutting_the_cord_to_test_energy_resilience

([50]) Reeves, M. M. (2019). Tyndall AFB continues rebuild effort one year after Hurricane Michael (accessed 1 July 2021). https://www.af.mil/News/Article-Display/Article/1985948/tyndall-afb-continues-rebuild-effort-one-year-after-hurricane-michael/

([51]) Goodman, A. (2018). While Trump Calls Climate Change a Hoax, Hurricane Michael Damaged US Fighter Jets Worth $6 Billion. Democracy Now! (accessed 1 July 2021). https://www.democracynow.org/2018/10/26/while_trump_calls_climate_change_a

([52]) Shapiro, A. (2019). Tyndall Air Force Base Still Faces Challenges In Recovering From Hurricane Michael. National Public Radio (accessed 1 July 2021). https://www.npr.org/2019/05/31/728754872/tyndall-air-force-base-still-faces-challenges-in-recovering-from-hurricane-micha?t=1620664980443

In Table 11, some possible measures to reduce risk and build resilience to windstorms are listed. The table is based on the studies of Girgin and Krausmann (2015), Karagiannis et al. (2019a) and Necci et al. (2018). It was supplemented with information from Das et al. (2013), Ferraioli et al. (2019), Hyater-Adams and DeYoung (2021), Roy and Ghosh (2019) and Roy and Kundu (2021).

Table 11. Example of possible measures to reduce risk and build resilience to windstorms.

Structural	Construct using impact-resistant building materials (e.g., precast concrete) that withstand wind loads;
	Secure building roof to foundation;
	Structure orientation to minimize exposure to most likely wind directions;
	Bury lifelines (e.g., electric wiring, telecommunications);
	Design, construct and maintain hurricane shelters;
	Design, construct and maintain debris barriers (e.g., fences);
	Periodical inspection, repair and maintenance of structures and lifelines (e.g., electric wiring, water and gas distribution);
	Strengthen electrical power grids (e.g., use of shape memory alloy dampers in transmission towers, implement redundancy, distributed generation);
	Use non-sparking (non-ferrous metals) materials wherever there is a handling or storage o flammable materials.
Non-structural	Use of braces, impact-resistant windows; hurricane screens, shutters, boarding, trim trees, close windows and doors;
	Protect against build-up of internal overpressure;
	Anchor equipment or place them below ground level (e.g., concrete vaults);
	Trim trees surrounding structures;
	On-site backup power generation and storage, transformer/battery/generator and spares reserve;
	Strengthening, anchoring and spill containment for piping and storage tanks (e.g., double shell, dikes, walls);
	Retrofitting of structures;
	Improved risk management (including compound events and cascading effects, high impact low probability and catastrophic events) beyond compliance, monitoring and early warning;
	Review and test contingency, emergency planning (including possible release of hazardous substances and occurrence of technological accidents), guidelines, communication protocols and systems;
	Targeted reassessment of safety margins (e.g., stress tests of power plants);
	Broad review of outage safety (e.g., critical infrastructure and military installations);
	Efficient pooling of resources across *EU Member States*;
	Restrictive land-use, relocation of existing structures and land acquisition;
	Interruption and/or relocation of activities (e.g., testing and training, loading and unloading of hazardous materials that could result in their release);
	Shutdown of lifelines (e.g., gas supply);
	Relocation of aircrafts, ships, tactical- and non-tactical vehicles;
	Evacuation of personnel;
	Partner with civilian entities in research, awareness raising, and capacity building.
Nature-Based Solutions	Restore coastal ecosystems (e.g., mangroves);
	Design and construct windbreaks.

The listed examples are in no particular order and there is no attempt to rank them.

5.5 Lightning, US

Type of negative impact	Direct
Influencing factors	Poor decision-making (military activities, repair and maintenance)
Consequences	Death, injury, business interruption, damage to property, economic loss, training and testing impaired

Lightning can lead to fatalities ([53]), injuries and lasting adverse health effects (e.g., *Centers for Disease Control and Prevention*, 2002; Shannon et al., 2017; Williams et al., 2018) ([54]). It can damage infrastructure ([55]), vehicles ([56]), aircraft ([57]) and equipment such as above-ground storage tanks ([58]), but also trigger wildfires ([59]), airborne debris ([60]), cascading effects such as power outages (National Grid ESO, 2019) ([61]) and technological accidents (e.g., the rainfall-induced flash flood case study presented in Section 5.2.3).

Since military activities (e.g., operations, training) take place irrespective of weather conditions, often in the field, their nature, frequency, timing and duration may increase lightning risk (Shannon et al., 2017; USATDC, 2002).

On August 2015, during a field training at *Camp Rudder*, *US Eglin Air Force Base*, Florida, US, lightning struck a nearby tree and the current flowed (side splashed) to soldiers (Shannon et al., 2017), even if they were in lightning lookdown (i.e., a procedure that instructs to keep physical distance of at least 3 m, and to lay down tactical gear, weapons and equipment when lightning is nearby). The event resulted in 44 injuries and the transport of patients to the Air Force Base emergency department, exceeding its available medical capacity (Shannon et al., 2017). Several of these patients experienced muscle, heart or kidney problems (Shannon et al., 2017)

Another example is that of August 2019, when a military ammunition depot near the city of Achinsk, Siberia, Russia, housing artillery shells and gunpowder, was allegedly struck by lightning, triggering several explosions that led to one fatality, dozens of people injured, thousands evacuated, and significant damage to nearby structures ([62, 63]). The ammunition stockpile lightning rods were damaged from a previous explosion, possibly due to human error, and could not provide effective protection anymore ([62, 63]).

In Table 12, some possible measures to reduce risk and build resilience to lightning are listed. The table is based on the studies of Bouquegneau (2007), Krausmann et al. (2017) and Necci et al. (2018).

([53]) Rohdem D. (1998). National Guardsman Killed by Lightning at Fort Dix. The New York Times (accessed 1 July 2021). https://www.nytimes.com/1998/05/04/nyregion/national-guardsman-killed-by-lightning-at-fort-dix.html
([54]) Martinez, M. (2011). Lightning strike at Mississippi military base sends 77 to hospital. CNN (accessed 1 July 2021). http://edition.cnn.com/2011/US/06/08/mississippi.lightning/
([55]) Thayer, R. L. (2019). Lightning Strikes Hit Runway of Already Damaged Offutt Air Force Base. Military.com (accessed 1 July 2021). https://www.military.com/daily-news/2019/04/12/lightning-strikes-hit-runway-already-damaged-offutt-air-force-base.html
([56]) Scavelli, M. (2020). Lightning causes car fire on Tinker AFB, no one injured. FOX25 (accessed 1 July 2021). https://okcfox.com/news/local/lightning-causes-car-fire-on-tinker-afb-no-one-injured
([57]) Boyer, D. (2020). How Air Force maintainers get a plane flying again after a lightning strike. Business Insider (accessed 1 July 2021). https://www.businessinsider.com/how-air-force-maintainers-repair-plane-again-after-lightning-strike-2020-7?r=US&IR=T
([58]) Holloway, L. (1996). Lightning bolt starts blaze in fuel tank in New Jersey. New York Times (accessed 1 July 2021). https://www.nytimes.com/1996/06/12/nyregion/lightning-bolt-starts-blaze-in-fuel-tank-in-new-jersey.html
([59]) Joint Base Lewis-McChord Garrison Public Affairs (2020). Lightning strike ignites wildfire at Yakima Training Center. US Army (accessed 1 July 2021). https://www.army.mil/article/238222/lightning_strike_ignites_wildfire_at_yakima_training_center
([60]) Seiger, T. (2020). Lightning strike causes chunk of road to fly through windshield, injuring 2. FOX News (accessed 1 July 2021). https://www.fox23.com/news/trending/lightning-strike-causes-chunk-road-fly-through-windshield-injuring-2/3A7L6IXF5FFO5C6UDE3SSHXJZE/
([61]) Morgan, S. (2019). Lightning strike to blame for massive UK power loss. EURACTIV (accessed 1 July 2021). https://www.euractiv.com/section/electricity/news/lightning-strike-to-blame-for-massive-uk-power-loss/
([62]) Pickrell, R. (2019). A Russian military ammo depot that blew up earlier this week just exploded again. Business Insider (accessed 1 July 2021). https://www.businessinsider.com/russia-struggles-to-get-military-ammo-depot-to-stop-exploding-2019-8?r=US&IR=T
([63]) Radio Free Europe/Radio Liberty (2019). New Blasts At Site Of Siberian Ammo Depot Tragedy Injure At Least Nine (accessed 1 July 2021). https://www.rferl.org/a/new-blasts-siberia-achinsk-ammunition-depot-russia/30101929.html

Table 12. Example of possible measures to reduce risk and build resilience to lightning.

Structural	Install lightning conductors (air terminals, down conductors, bonding and grounding);
	Periodical inspection, repair and maintenance of lightning conductors.
Non-structural	Install and maintain lightning arresters, power surge protection devices and circuit breakers;
	Protection of safety critical systems or equipment from hydrostatic, hydrodynamic and wave loads or water ingress (e.g., waterproofing, appropriate design and placement);
	Improved risk management (including compound events and cascading effects, high impact low probability, catastrophic and nuisance events) beyond compliance, monitoring (e.g., lightning detector) and early warning;
	Review and test contingency, emergency planning (including possible occurrence of technological accidents), guidelines, communication protocols and systems;
	Interruption and/or relocation of activities (e.g., testing and training);
	Partner with civilian entities in research, awareness raising, and capacity building.
Nature-Based Solutions	—

The listed examples are in no particular order and there is no attempt to rank them.

5.6 Wildfire, USA

Type of negative impact	Direct and indirect
Influencing factors	Heatwave, drought
Consequences	Death, business interruption, damage to property (e.g., military land), training and testing impaired

The US Air Force Base Vandenberg is over 397 km^2 with 56 km of coastline, mostly undeveloped land with different types of vegetation. The military installation plays a critical role in national defence, and wildfires have been threatening the ability to fulfil its mission (Staub, 2011). The combination of vegetation types, rugged topography and ignition sources create the potential for wildfires within the military installation. For these reasons, in 1981, a wildland fuel management plan was implemented (Hickson, 1988).

The *US Air Force Base Vandenberg* has its own fire department that responds to wildfire hazards frequently, but in some cases its capability is exceeded and interagency support is required. For example, in 2010 the military installation fire department responded to 63 wildfires (unclear if within the installation; Figure 26), some of which threatened mission-critical infrastructure (Staub, 2011). Examples of major historical wildfires within the military installation include:

- In December 1977, the Honda Canyon Fire resulted in ca. 33 km^2 of burned area (Hickson, 1988). Fire weather consisted of drought, humidity of 14% or less and pre-frontal winds with 18 to 34 m/s. A downed power line was most likely the ignition source. Four personnel lost their lives (Staub, 2011), heavy military and civilian involvement was needed to control the fire;
- In September 2016, the Canyon Fire resulted in ca. 52 km^2 of burned area. According to the *California Department of Forestry and Fire Protection* (CAL FIRE) ([64]), it was the seventh largest fire in terms of burned area that year. Fire weather consisted of persistent drought since 2011 (Diffenbaugh et al., 2015), high density of dry vegetation and warm temperatures. Other relevant factors included ignition, of source unknown, in a location inaccessible to fire fighters and complex topography. This wildfire illustrates well the extent that a fire can reach and some of its adverse indirect effects, for example the severe degradation of military land, disruption of rocket launches due to fire threat, and disruption of activities due to widespread power outages that forced the use of generators (DOD, 2019a).

In Table 13, some possible measures to reduce risk and build resilience against wildfires are listed. The table is based on the studies of Kern and Krausmann (2020), Krausmann and Mushtaq (2006) and Ricci et al. (2021).

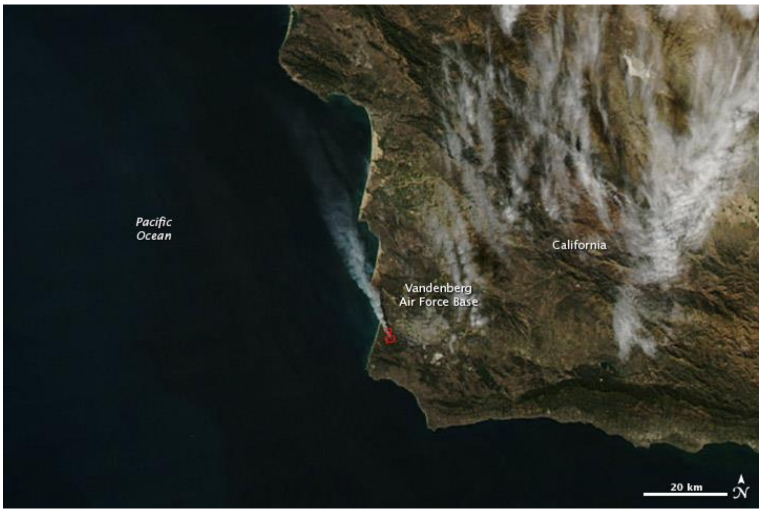

Figure 26. Fire near the *US Air Force Base Vandenberg,* California, in October 2010. Source: NASA MODIS Rapid Response Team, GSFC

([64]) CAL FIRE. 2016 Incident Archive (accessed 1 July 2021). https://www.fire.ca.gov/incidents/2016/

Table 13. Example of possible measures to reduce risk and build resilience to wildfires.

Structural	Fireproofing existing structures (e.g., fire-resistant materials, glazing, armoured walls and roof);
	Strengthen electrical power grids (e.g., implement redundancy, distributed generation);
	Avoid floating roof storage tanks for flammable materials.
Non-structural	On-site backup power generation and storage, and transformer/battery/generator and spares reserve;
	In case of fire disconnect gutters, downpipes and heating, ventilation, and air conditioning when possible to avoid clogging or penetration of ash to interiors;
	Perimeter defences (e.g., vegetation clearance) and adapt safety distances between critical equipment and vegetation;
	Reduction of the frequency and intensity of use of real munitions/artillery in fire-prone areas, especially during conditions favourable for ignition and propagations;
	Improved risk management (including compound events and cascading effects) beyond compliance and early warning;
	Review and test contingency, emergency planning (including possible occurrence of technological accidents), guidelines, communication protocols and systems;
	Broad review of outage safety (e.g., critical infrastructure and military installations);
	Efficient pooling of resources across *EU Member States*;
	Restrictive land-use (e.g., facilities and equipment distant from vegetation and slopes), relocation of existing structures and land acquisition;
	Interruption and/or relocation of activities (e.g., testing and training);
	Shutdown of fuel supply lines and de-inventorying of storage tanks of hazardous substances;
	Efficient cleaning of drainage systems before an event, but also after to avoid floods;
	Partner with civilian entities in research, awareness raising, and capacity building.
Nature-Based Solutions	Integrated fire management (e.g., controlled burns that favour fire-adapted species, use of fuel breaks including natural barriers, forest biomass removal, controlled grazing, fire ecology).

The listed examples are in no particular order and there is no attempt to rank them.

5.7 Rainfall-induced landslide, Vietnam

Type of negative impact	Direct
Influencing factors	Heavy rainfall
Consequences	Death, injury, damage to property, economic loss, operational readiness, training and testing impaired

In October 2020, during the monsoon season and the ongoing COVID-19 pandemic, Vietnam experienced a succession of tropical cyclones that caused prolonged heavy rainfall (e.g., between 5 and 10 October, 1520 and 1888 mm of rain were recorded in Huong Linh, Quang Tri province, and A Luoi, Thua Thien-Hue province, respectively) ([65]), severe floods and rainfall-triggered landslides (Van Tien et al, 2021a, b) ([65, 66, 67, 68]). As a result, millions of people were affected, more than 357 people died or are missing, 876 were injured, and damage to property and infrastructure was extensive according to the Vietnam Disaster Management Authority. Roads and bridges were heavily damaged, power outages in the affected areas led to communications being hampered ([69]).

In the Thua Thien Hue Province, 13 members of a rescue team, mostly soldiers, were buried by a landslide at a ranger station and did not survive ([70]). A few days later, in the Quang Tri Province, another 22 soldiers were also buried by a landslide at an army barracks, and they too did not survive ([71, 72, 73]). As shown by the event photos, facilities inside the army barracks were partially buried and damaged, and accesses to the installation were blocked causing difficulties for the rescue teams ([71, 72]).

Based on the study of the Norwegian Geotechnical Institute ([74]) some possible measures to reduce risk and build resilience to landslides are listed in Table 14.

([65]) FloodList (2020). Vietnam – More Than 100 Lives Lost in Central Region Floods and Landslides (accessed 1 July 2021). http://floodlist.com/asia/vietnam-floods-central-region-death-toll-october-2020

([66]) JBA Risk Management (2020). Vietnam Floods: A Tale of Six Cyclones (accessed 1 July 2021). https://www.jbarisk.com/flood-services/event-response/vietnam-floods/

([67]) Lampard, A. (2020). Vietnam floods and landslides displace 90,000 people as new cyclone nears. The Guardian (accessed 1 July 2021). https://www.theguardian.com/world/2020/oct/19/vietnam-floods-and-landslides-displace-90000-people-as-new-cyclone-nears

([68]) ASEAN Coordinating Centre for Humanitarian Assistance on disaster management (2020). Viet Nam, Flooding and Landslides in Central Provinces (11:51 Oct 10 2020). ReliefWeb (accessed 1 July 2021). https://reliefweb.int/report/viet-nam/viet-nam-flooding-and-landslides-central-provinces-1151-oct-10-2020

([69]) International Federation of Red Cross and Red Crescent Societies (2021). Vietnam: Floods - Operation Update Report – 6 Month Update, Emergency Appeal n° MDRVN020 (accessed 1 July 2021). https://reliefweb.int/report/viet-nam/vietnam-floods-operation-update-report-6-month-update-emergency-appeal-n-mdrvn020

([70]) VnExpress (2020). Bodies of 13 rescue team members retrieved from landslide rubble (accessed 1 July 2021). https://e.vnexpress.net/news/news/bodies-of-13-rescue-team-members-retrieved-from-landslide-rubble-4177127.html

([71]) VnExpress (2020). Bodies of 22 soldiers killed in Quang Tri landslide found (accessed 1 July 2021). https://e.vnexpress.net/news/news/bodies-of-22-soldiers-killed-in-quang-tri-landslide-found-4178691.html

([72]) Hoang Phuong, H. T. (2020). Quang Tri mountain landslide buries 22 army personnel (accessed 1 July 2021). https://e.vnexpress.net/news/news/quang-tri-mountain-landslide-buries-22-army-personnel-4178294.html

([73]) VnExpress (2020). Central Vietnam: a month in tragedies (accessed 1 July 2021). https://e.vnexpress.net/news/news/central-vietnam-a-month-in-tragedies-4185767.html

([74]) Norwegian Geotechnical Institute (2016). LaRiMiT (Landslide Risk Mitigation Toolbox) – Mitigation Measures (accessed 1 July 2021). https://www.larimit.com/mitigation_measures/

Table 14. Example of possible measures to reduce risk and build resilience to landslides.

Structural	Slope stabilization (e.g., gabions, soil nail, bolting, strand anchors, dowels, harnessing, barrettes, piles, caissons, sealing tension cracks);
	Slope modification (e.g., smoothing, impervious facing, removal or distribution of unstable materials, compaction, mixing materials);
	Landslide control (e.g., barriers, gully breaks, ditches and embankments, berms, check dams, baffles, rock sheds);
	Drainage improvement (e.g., diversion channels, pipeworks, channel lining, horizontal drains, deep trenches, well systems, tunnels).
Non-structural	Improved risk management (including compound events and cascading effects) beyond compliance, monitoring (e.g., slope movement or pipe strain sensors) and early warning;
	Review and test contingency, emergency planning (including possible release of hazardous substances and occurrence of technological accident), guidelines, communication protocols and systems;
	Restrictive land-use (e.g., buildings distant from slopes), relocation of existing structures and land acquisition;
	Interruption and/or relocation of activities (e.g., testing and training);
	Partner with civilian entities in research, awareness raising, and capacity building.
Nature-Based Solutions	Slope stabilization (e.g., revegetation, gratings, live piles);
	Slope modification (e.g., hydroseeeding, turfing, live stakes, slope planting, brush mattresses, soil nail, live crib wall, drainage blanket, geotextile, rubble, rock dentition, terracing);
	Landslide control (e.g., live check dams).

The listed examples are in no particular order and there is no attempt to rank them.

5.8 Thawing permafrost, Russia

Type of negative impact	Direct
Influencing factors	Poor decision-making (design, monitoring, retrofitting, maintenance and repair)
Consequences	Infrastructure and service disruption, business interruption, damage to property, economic loss, training and testing impaired (e.g., degraded military land), environmental pollution

The effects of climate change on permafrost and on the thawing layer can have severe impacts on military installations (Nelson et al., 2002; Streletskiy et al, 2019; Suter et al, 2019). In the US, the military have several installations in areas of discontinuous permafrost, namely in Alaska, and must cope with an increasing rate of thawing and a changing landscape (Comiso and Hall, 2014; Rowland et al., 2010; USARC, 2003). Testing and training grounds may become unusable (USARC, 2003), and indirect impacts can result from affected infrastructure serving the military such as roads, trails and railways, bridges, buildings, utilities (e.g., power plants, power grids, gas and oil pipelines, fuel storage), and airstrips (Hjort et al., 2018; USARC, 2003). Concerns also include accidents such as spills of hazardous materials (Anisimov and Reneva, 2006) and exposure of waste (ACIA, 2004; Colgan et al., 2016).

For example, in May 2020 an above-ground POL tank ruptured in Norilsk, Russia, releasing 2.12×10^4 tons of diesel. The causes were attributed to thaw subsidence, reduction in adfreeze and bearing capacity, creep settlement and failure of concrete piles, but also mismanagement and risk underestimation to some extent (ERM, 2020). Although this POL tank belonged to a power plant, military installations often house them for storage of different fuel types.

Another example is that of pipelines which are typically used to supply military installations with fuel or gas. Approximately 35,000 pipeline accidents are reported annually in West Siberia, of which ca. 21% can be attributed to pipeline deformation due to changes in ground stability. In the Komi Republic in 1994 more than 1.6×10^5 tons of oil were released following six ruptures due to thawing permafrost (Streletskiy et al., 2012). More recently, Hjort et al. (2018) estimated that ca. 32% of oil and gas pipelines (e.g., Trans-Alaska Pipeline System) may be considerably exposed to thawing permafrost, depending on the GHG emission scenario considered (in this case the *Representative Concentration Pathway* [RCP] 2.6, RCP 4.5 or RCP 8.5; van Vuuren, et al., 2011), and noting the high degree of uncertainty.

The majority of structures in permafrost regions were designed for baseline conditions, with a lifespan of ca. 50 years, and rely on the bearing capacity of the permafrost. If this bearing capacity decreases with warming (e.g., the observed decline of 40 to 50% in Siberian settlements since 1960; AMAP, 2017), an effect unaccounted for, it can weaken foundations and threaten structural integrity (AMAP, 2017; Hjort et al., 2018; Streletskiy et al., 2012; USARC, 2003).

In Table 15, measures to reduce risk and build resilience to thawing permafrost are listed. They are based on the studies of AMAP (2011), Darrow and Jensen (2016), ERM (2020) and Beer et al. (2020). These measures may need to be implemented in a continuous manner and over long periods, while rapid changes may require more contingency planning (AMAP, 2017).

Table 15. Example of possible measures to reduce risk and build resilience to thawing permafrost.

Structural	Improved design and construction for changing bearing capacity of permafrost;
	Use of winter-ventilated ducts, active or passive cooling systems (e.g., air convection embankments) and thermosiphons to remove heat from the permafrost;
	Structural elevation (e.g., deep piles to decouple frozen ground from the active and latent heat of structures;
	Increase bedrock support in foundations;
	Insulated and refrigerated buried pipelines;
	Under ventilation of above-ground storage tanks;
Non-structural	Strengthening and spill containment for piping and storage tanks (e.g., double shell, dikes);
	Retrofitting of structures;
	Improved risk management (including cascading effects) beyond compliance and monitoring (e.g., permafrost temperature sensors);
	Review and test contingency, emergency planning (including possible release of hazardous substances and occurrence of technological accident), guidelines, communication protocols and systems;
	Targeted reassessment of safety margins (e.g., stress tests of power plants);
	Broad review of outage safety (e.g., critical infrastructure and military installations);
	Restrictive land-use (e.g., buildings only where long term bearing capacity is predicted to hold, or its loss can be mitigated) and land acquisition;
	Relocation of activities (e.g., testing and training);
	Partner with civilian entities in research, awareness raising, and capacity building.
Nature-Based Solutions	Rewilding permafrost regions.

The listed examples are in no particular order and there is no attempt to rank them.

Box 7. Additional notes on permafrost thawing.

1) The effects of permafrost thawing are not necessarily abrupt, but can develop gradually (Anisimov and Reneva, 2006);

2) Infrastructure itself changes ground conditions, something that is generally accounted for and distinct from changes induced by global warming (AMAP, 2017; Anisimov and Reneva, 2006; Streletskiy et al, 2019).

6 Impacts of Geophysical Hazards and Space Weather – Case Studies

6.1 Geophysical hazards

6.1.1 Earthquakes

Type of negative impact	Direct and Indirect
Influencing factors	—
Consequences	Damage to property, economic loss, operational readiness, training and testing impaired

The *US Naval Air Weapons Station China Lake*, located in California in the high desert at the base of Sierra Nevada Mountain Range, ca. 732 m above mean sea level, is over 4500 km², with ca. 95% of undeveloped and undisturbed land. It consists of 2132 buildings and 529 km of paved roads. The Naval Air Weapons Station provides shore-based infrastructure, military installation operating services, safety and security, range and airfield support to Navy's research, development, acquisition, mission test and evaluation, training, fleet support, and natural, cultural and historical stewardship. It is the Navy's largest landholding, established in 1943, with ca. 8000 workforce.

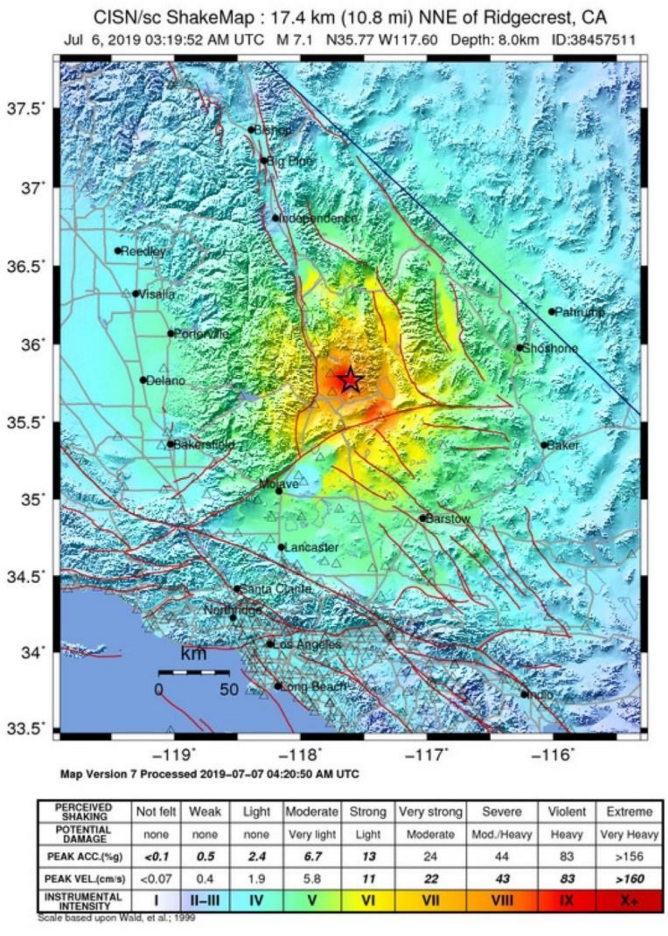

Figure 27. ShakeMap for the 7.1 Mw earthquake that occurred on 5 July 2019, with epicentre (marked with a star) within the Naval Air Weapons Station China Lake. Source: USGS

In 2019, a sequence of earthquakes and aftershocks lasting up to 31 July, known as the 2019 Ridgecrest earthquake sequence, took place mostly within the Naval Air Weapons Station, significantly impacting it, as well as the cities of Ridgecrest and Trona and the Searles Valley region (EERI, 2020; Brandenberg et al., 2019; Ross et al., 2019). The sequence included a foreshock on 4 July of 6.4 moment magnitude (Mw) and epicentre ca. 18 km east-northeast of the city of Ridgecrest (EERI, 2020); and a main shock on 5 July, of 7.1 Mw and epicentre ca. 10 km northwest of the previous one (EERI, 2020; Ross et al., 2019). The focal mechanism of the main shock corresponds to a steeply dipping, northwest-trending, right-lateral strike-slip fault (EERI, 2020; Ross et al., 2019). The corresponding *US Geological Survey* (USGS) ShakeMap is presented in Figure 27.

As a result of the earthquake sequence, the Naval Air Weapons Station was unable to undertake its mission. Overall, the earthquake sequence resulted in ca. US$5.2 billion of damage within the Naval Air Weapons Station, and ca. US$2.2 billion corresponding to building replacement costs. Although details about damage within the Naval Air Weapons Station are not easily found in the public domain, damage outside, such as those presented in Figure 28, are well documented (e.g., EERI, 2020; Brandenberg et al., 2019; Mosalam et al., 2019).

Figure 28. Access road to the Naval Air Weapons Station China Lake with transverse cracks and pavement misalignment due to ca. 2.5 m right-lateral motion along the primary rupture. Damage associated with the 7.1 Mw earthquake (Brandenberg et al., 2019). Source: Ken Hudnut/USGS

In Table 16, measures to reduce risk and build resilience to earthquakes are listed. The table is based on the studies of Arcidiacono et al. (2014), Girgin and Krausmann (2015), Karagiannis et al. (2017), Krausmann (2014), Necci et al. (2019) and Piccinelli and Krausmann (2013). It is supplemented by information from Ferraioli et al. (2019), Roy and Ghosh (2019), Roy and Kundu (2021), EERI (2020) and Gantes and Melissianos (2016).

Table 16. Examples of possible measures to reduce risk and build resilience to earthquakes.

Structural	Seismic design and earthquake-resistant construction (e.g., reinforced concrete, fibre material, shape memory alloys, external steel cages, cross-bracing, seismic base isolation and dampers, separation joints between structures, reinforce walls, use shear walls, infilling of openings, confine columns, stiffening floors; for structural protection);
	Strengthen electrical power grids (e.g., seismic design of transformers according to international standards, use of shape memory alloy dampers in transmission towers, implement redundancy, distributed generation) and use of micro-grids;
	Use of buried heavy-walled welded steel or polyethylene pipes, lining, place pipes within culverts, avoid low pressure pipes, use flexible connections (e.g., joints, tank-pipe connections), emergency valves, zig-zag configuration, backfill trenches with pumice, and pipe wrapping with geotextile;
	Use storage tanks with thicker walls;
	Use non-sparking (non-ferrous metals) materials wherever there is a handling or storage of flammable materials;
	Periodical inspection, repair and maintenance of structures and lifelines (e.g., electric wiring, water and gas distribution).
Non-structural	Relocation of equipment to ground floor or below ground (e.g., ground power feeders);
	On-site backup power generation and storage, transformer/battery/generator and spares reserve;
	Secure fixtures, anchor equipment, no shelving of heavy items, use of drums instead of intermediate bulk containers in storage racks, install latches on drawers and cabinets, store flammable substances in closed cabinets, tie backs for building heavy exterior elements (e.g., parapets, chimney);
	Strengthening, anchoring and spill containment measures for piping and storage tanks (e.g., double shell, dykes, walls).
	Retrofitting of structures;
	Power grid operation (load priority and shedding);
	Improved risk management (including cascading effects) beyond compliance, monitoring (e.g., structural and seismic monitoring sensors), and early warning;
	Review and test contingency, emergency planning (including possible occurrence of technological accidents), guidelines, communication protocols and systems;
	Targeted reassessment of safety margins (e.g., stress tests of power plants);
	Broad review of outage safety (e.g., critical infrastructure and military installations);
	Efficient pooling of resources across *EU Member States*;
	Restrictive land-use;
	Interruption of activities (e.g., testing and training, loading and unloading of hazardous materials that could result in their release);
	Evacuation of personnel;
	Partner with civilian entities in research, awareness raising, and capacity building.
Nature-Based Solutions	—

The listed examples are in no particular order and there is no attempt to rank them.

6.1.2 Volcanic activity, Philippines

Type of negative impact	Direct and indirect
Influencing factors	Seismic activity, ash accumulation, wind, heavy rainfall, lahars, poor decision–making (land-use planning, risk underestimation)
Consequences	Death, injury, evacuation, infrastructure and service disruption, business interruption, damage to property, economic loss, operational readiness, training and testing impaired, political shock

In June 1991, Mount Pinatubo in the Philippines, ca. 90 km to the northwest of capital Manila, gave rise to the world largest volcanic eruption in 50 years (Figure 29) (Newhall and Raymundo, 1997).

Figure 29. Mount Pinatubo eruption view from the US Air Force Base Clark in the Philippines. Source: TSGT. Val Gempis/DOD

The event started with a series of earthquakes from mid-March onwards and a series of four vertical eruptions, the first lasting 38 min, generating a column of ash as high as 14 km and high-amplitude seismic activity. On June 15, Tropical Cyclone Yunya made landfall, which helped to disperse ash and reach near-zero visibility in the region. The same day, climax was reached with an eruption lasting for about nine hours, reaching 34 km height, 400 km of diameter, accompanied by high-amplitude seismic activity, lahars, pyroclastic flows, eruption deposits of ca. 10.4 km^3 (total volume), and the collapse of the summit producing a caldera of 2.5 km of diameter (Koyaguchi and Tokuno, 1993; Newhall and Raymundo, 1997). There was also the emission of 17 Mt of sulphur dioxide that had a cooling effect in the Northern Hemisphere and rapid ozone depletion in the Southern Hemisphere during the two subsequent years (Newhall and Raymundo, 1997). The plume and earthquakes progressively declined until late July, with occasional events until September (Newhall and Raymundo, 1997).

At that time, more than 30,000 people lived in the vicinity of Mount Pinatubo (Newhall and Raymundo, 1997). Together with the cyclone, the volcanic eruption resulted in more than 200 fatalities (more than 840 according to the USGS) and injuries, mostly because of collapsing structures. It also resulted in extensive property and infrastructure damage such as bridges, irrigation channels, and roads, due to the weight of the ash-saturated rain (load of 150-200 mm, ca. 400 kg/m^2), the winds and seismic activity (Newhall and Raymundo, 1997). ([75, 76]) Additionally, aircrafts flying through the cloud of ash and acid gases were damaged and some experienced loss of power (Newhall and Raymundo, 1997). Total economic losses for this event were estimated at more than US$400 million. Costs to transportation (ca. US$42 million), communications

([75]) Westby, E. and Phillips, D. (2016). Remembering Mount Pinatubo 25 Years Ago: Mitigating a Crisis. USGS (accessed 1 July 2021). https://www.usgs.gov/news/remembering-mount-pinatubo-25-years-ago-mitigating-crisis

([76]) Halvorsen, H. E. (2017). AIR FORCE HISTORY: The Evacuation of Clark Air Force Base (accessed 1 July 2021). https://www.tinker.af.mil/News/Article-Display/Article/1218915/air-force-history-the-evacuation-of-clark-air-force-base/

(ca. US$ 0.5 million), energy (ca. US$2 million), water resources (ca. US$58 million), and social infrastructure (ca. US$39 million) amounted to ca. US$141 million (Newhall and Raymundo, 1997).

US Air Force Base Clark, located ca. 25 km to the east of the volcano, the most populated US overseas military installation, *US Naval Base Subic Bay* and *US Naval Air Station Cubi Point*, ca. 40 km to the southwest, suffered significant damage (Newhall and Raymundo, 1997). More than 100 buildings collapsed or were severely damaged (some had timber frames, unbraced supporting walls or columns, unsupported roof overhangs, and 75% had long-span roofs), drainage and sewer systems were clogged, and power plants were damaged (Figure 30) (Newhall and Raymundo, 1997). ([76, 77])

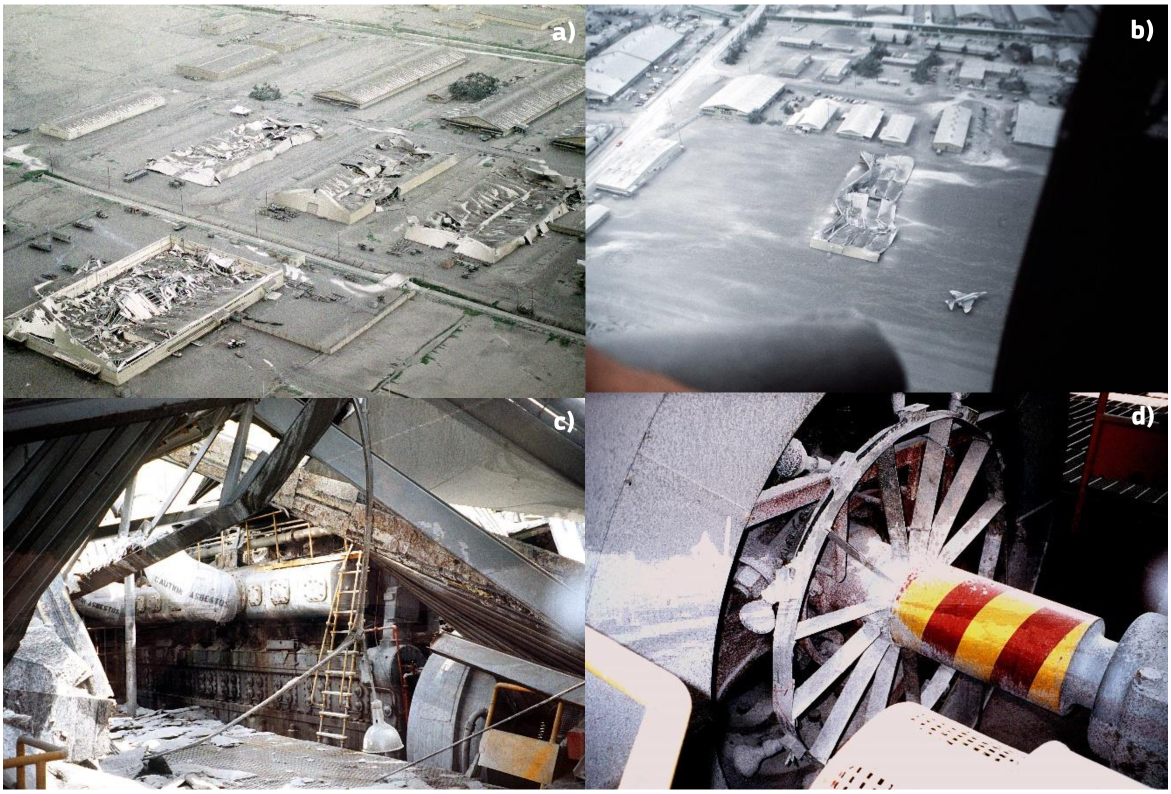

Figure 30. Severe damage to US military overseas installations in the Philippines caused by the volcanic eruption of Mount Pinatubo and exacerbated by Tropical Cyclone Yunya in 1991. a) Aerial view of ash covering the military installation; b) Ash covering collapsed aircraft hangar; c) Collapsed roof in power plant with generating equipment underneath; d) Volcanic ash covering electrical power generator. Sources: a) Tech. Sgt. Val Gempis/DOD; b), c) and d) unknown/DOD

The event initiated *Operation Fiery Vigil*, the largest evacuation in US history (15,000 personnel) since 1975, and, ultimately, it led to the handing over of the *US Air Force Base Clark* to the government of the Philippines on November 1991. It is important to note that since Mount Pinatubo had been inactive for more than 500 years the military were initially doubtful about the possibility of an eruption. ([76, 78]).

Based on the studies of Milazzo et al. (2013a, b) and Pierson et al. (2014) some possible measures to reduce risk and build resilience to volcanic activity are listed in Table 17.

([77]) Volcano Ashfall Impacts Working Group. Pinatubo 1991 (accessed 1 July 2021). https://volcanoes.usgs.gov/volcanic_ash/pinatubo_buildings.html

([78]) Anderegg, C. R. (2000). Clark Digs Out of the Ashes. Air Force Magazine (accessed 1 July 2021). https://www.airforcemag.com/article/0300clark/

Table 17. Examples of possible measures to reduce risk and build resilience to volcanic activity.

Structural	Design, construct and maintain roofs, or reroof, to withstand higher ash or water-saturated ash loads (e.g., design load, geometry, steep pitch roofs, short-roof spans, smooth corrosion-resistance and -coating materials, uniform versus non-uniform load considerations) and avoid roof elements that lead to the accumulation of volcanic ash (e.g., chimneys, parapets);
	Improve corrosion resistance, including coating and inhibitors of structures, lifelines and equipment;
	Structure orientation to minimize exposure to most likely wind directions and, thus, ash accumulation;
	Periodical inspection, repair and maintenance of structures (e.g., roofs);
	Construct exclusion dikes to enclose and protect infrastructure from lahar impact.
Non-structural	Sealing/cover of critical equipment, windows, doors, air intakes (e.g., stronger filters), ducts, storage tanks;
	Decontamination rooms for clean entry into facilities;
	Disconnect gutters, downpipes and heating, ventilation, and air conditioning when possible to avoid clogging or penetration of ash to interiors;
	On-site backup power generation and storage, transformer/battery/generator and spares reserve;
	Retrofitting of structures;
	Improved risk management (including cascading effects) beyond compliance, monitoring (e.g., structural and seismic monitoring sensors), and early warning;
	Review and test contingency, emergency planning (including possible occurrence of technological accidents), guidelines, communication protocols and systems;
	Broad review of outage safety (e.g., critical infrastructure and military installations);
	Efficient pooling of resources across *EU Member States*;
	Restrictive land-use (e.g., buildings distant from volcanos and their potential impact paths), relocation of existing structures and land acquisition;
	Interruption and/or relocation of activities (e.g., testing and training, loading and unloading of hazardous materials that could result in their release);
	Relocation of aircrafts, tactical- and non-tactical vehicles;
	Evacuation of personnel;
	Efficient cleaning of ash including drainage systems;
	Partner with civilian entities in research, awareness raising, and capacity building.
Nature-Based Solutions	—

The listed examples are in no particular order and there is no attempt to rank them.

Box 8. A note on possible measures to reduce risk and build resilience to volcanic activity.

Since volcanic activity may possibly involve seismic activity the possible measures to reduce risk and build resilience to earthquakes also apply (Table 16)

6.1.3 Tsunami, India

Type of negative impact	Direct
Influencing factors	—
Consequences	Death, evacuation, infrastructure and service collapse, business interruption, damage to property, economic loss, operational readiness, training and testing impaired

In December 2004, a 9.1 Mw tsunamigenic earthquake occurred between the tectonic plates of India and Burma in Northern Sumatra, Indonesia, with mainshocks predominantly thrust faulting with 8° dip, 329° strike and 110° rake (Lay et al., 2005). The resulting tsunami that devastated entire communities and led to hundreds of thousands of fatalities in Indonesia, Sri Lanka, India, Thailand, and many other regions combined, was primarily caused by the vertical displacement of the seafloor, uplift towards the trench and dewdrop towards the coast. ([79]) Maximum tsunami wave heights were reached in Aceh province, Indonesia, with 51 m, while Thailand experienced up to 20 m, Sri Lanka and India up to 12 m, and Somalia, more than 5000 km away, 10 m ([80]).

The Indian Air Force Base located in the island of Car Nicobar, the northernmost of the Nicobar Islands, was completely reduced to rubble by the tsunami. Hundreds of military personnel and their families lost their lives. The militaries assigned to replace, relief and rebuild operations were overwhelmed when they arrived to the atoll. The helicopter station and runaway, the highest point within the military installation, and other facilities such as schools and guest houses were completely destroyed. Water supply and communications were not available as a result of the tsunami. ([81])

The *US Navy Support Facility Diego Garcia* on the southernmost island in the Chagos Archipelago, British Indian Ocean Territory, received a warning at least 30 min before the tsunami. The tsunami did not affect personnel, facilities or operations since bathymetry around the atoll did not produce significant shoaling. ([82])

Box 9. A note on possible measures to reduce risk and build resilience to tsunamis.

Since the possible measures to reduce risk and build resilience to tsunamis are somehow similar to those for coastal floods (Table 7), a specific list will not be presented in this section.

([79]) USGS. Tsunami Generation from the 2004 M=9.1 Sumatra-Andaman Earthquake (accessed 1 July 2021). https://www.usgs.gov/centers/pcmsc/science/tsunami-generation-2004-m91-sumatra-andaman-earthquake?qt-science_center_objects=0#qt-science_center_objects

([80]) NOAA. Tsunami Wave Run-ups: Indian Ocean – 2004 (accessed 1 July 2021). https://sos.noaa.gov/datasets/tsunami-wave-run-ups-indian-ocean-2004/

([81]) Masih, A. Air Force base rises from tsunami wreckage. Rediff.com 2005 (accessed 1 July 2021). https://www.rediff.com/news/2005/jun/24spec1.htm

([82]) Norton-Taylor, R. (2005). US island base given warning – Bulletins sent to Diego Garcia 'could have saved lives'. The Guardian (accessed 1 July 2021). https://www.theguardian.com/world/2005/jan/07/tsunami2004.uk

6.2 Space weather, US and Vietnam

Type of negative impact	Direct
Influencing factors	Limited knowledge, technology underdevelopment
Consequences	Infrastructure and service disruption, political shock

According to Knipp et al., (2016), the May 1967 space weather storm was one of the largest of the 20th century. It occured during the Cold War, marked by a nuclear arms race. The storm first triggered a series of radio bursts disrupting military radio and satellite communications, radars, and command and control (e.g., the DOD high-altitude *US Ballistic Missile Early Warning System*), particularly in the Polar Regions. A record-breaking category G5 geomagnetic storm (-387 nT), on NOAA's space weather scales ([83]), overlapped these disruptions, despite evidence for large GICs. Given the politically tense atmosphere, the disruptions were interpreted as enemy radar jamming and deception, a potential act of war. If it were not for the scientists' arguments, even with limited data, that the disruptions were due to abnormal Sun activity, perhaps a bomber attack would have been launched without the possibility for a recall due to downed communications.

Knipp et al. (2018) reported that in August 1972 a series of very intense solar flares, that possibly cleared the path for a geomagnetic storm that reached Earth 14.6 hours later, created a near category S5 radiation storm (Jiggens et al., 2014), on NOAA's space weather scales ([83]). Communication and electrical power systems were severely affected, and a DOD satellite suffered a mission-ending power failure. In August 1972, the Vietnam War was still ongoing and the US decided to blockade Vietnam in order to force the country to the negotiating table and end the war. In this context, the US Navy deployed a large number of sea mines (possibly in the thousands) that suddenly and unintentionally detonated. The US Navy attributed the explosions to solar storms magnetic perturbations that exceeded amplitude, polarity, rate of change, and/or gradient thresholds.

The previous two events that were illustrated brought significant changes to the DOD (e.g., the hardening of power and communications against radiation), which possibly created the basis for other civilian innovations, and to US policy on addressing space weather threats (e.g., The White House, 2016).

Based on the studies of Piccinelli and Krausmann (2015), Karagiannis et al. (2017), Krausmann (2011), Krausmann et al. (2013, 2014, 2015, 2016a) and Yu et al. (2019), some measures to reduce risk and build resilience to space weather are listed in Table 18.

Table 18. Examples of possible measures to reduce risk and build resilience to space weather.

Structural	Strengthen electrical power grids (e.g., use 3-limbed, 3-phase core transformers, transformer protection relays, neutral current blocking devices, distributed generation, reduce dependency on high-voltage transmission, optimise network interconnections and configuration) and use of micro-grids;
	Measures to mitigate the degradation of global navigation signals;
	Pipelines corrosion protection, control of potentiostats and optimal distribution of insulating flanges.
Non-structural	On-site backup power generation and storage, transformer/battery/generator and spares reserve.
	Power grid operation (load priority and shedding, shunt reactor optimization, re-dispatching, temporary disconnection of transformers, extra reactive power, rolling blackouts, quick return to service of equipment, delaying maintenance);
	Improved risk management (including cascading effects) beyond compliance, monitoring (e.g., Deep Space Climate Observatory [DSCOVR], Solar Ultraviolet Imager), and early warning;
	Review and test contingency, emergency planning (including possible occurrence of technological accidents), guidelines, communication protocols and systems;
	Targeted reassessment of safety margins (e.g., stress tests of power plants);
	Broad review of outage safety (e.g., critical infrastructure and military installations);
	Partner with civilian entities in research, awareness raising, and capacity building.
Nature-Based Solutions	—

The listed examples are in no particular order and there is no attempt to rank them.

([83]) NOAA. NOAA Space Weather Scales (accessed 1 July 2021). https://www.swpc.noaa.gov/noaa-scales-explanation

7 Towards a more resilient EU Defence: gaps and recommendations

7.1 Gaps

7.1.1 Governance

The EU has a number of legislative and non-legislative acts currently in force that prompted *EU Member States* to step up resilience to natural hazards and climate change by setting out rules uniformly (Regulations) or establishing objectives (Directives), formulating targeted decisions, and issuing recommendations. Some of these have direct or indirect repercussions on the military.

The *European Union Civil Protection Mechanism* (UCPM), Decision No 1313/2013/EU and Decision (EU) 2019/420), is a key instrument for cooperation (e.g., exercising, resource pooling, knowledge exchange) in disaster risk management, within which *EU Member States* prepare National Risk Assessments (NRAs), supported by specific reporting guidelines (EC, 2015, 2019b), that also account for critical infrastructure. To support the UCPM, the EU earth observation *Copernicus* programme, Regulation (EU) 2021/696, provides geospatial information, mapping and warnings, crucial to inform decision-making without depending on external providers.

Importantly, Council Directive 2008/114/EC, requires *EU Member States* to increase the protection of critical infrastructure "of vital societal functions", including at the European level (EC, 2006), against multiple hazards and threats. However, acknowledging the dynamic nature of the risk landscape and the deepening of cross-sector dependencies, it is argued that this framework is no longer fully fit-for-purpose or future-proof and a new directive is being discussed to give greater emphasis on resilience and dependencies (EC, 2020c).

In the case of the energy sector, action by *EU Member States* on disaster risk management and the security of energy supply, including ownership concerns, is prompted by Regulation (EU) 2019/941, Commission Regulation (EU) 2017/2196 and the *European Energy Security Strategy* (EC, 2014) that at the same time recognizes a trade-off between efficiency and resilience.

Complementarily, Council Directive 2014/87/Euratom and Directive 2009/71/Euratom, establish a framework for the safety of nuclear installations accounting for multiple hazards particularly in stress testing. On the other hand, the prevention of major industrial accidents and the mitigation of their consequences is handled by the Seveso-III Directive (Directive 2012/18/EU) that compels operators to implement safety and risk-reduction measures and to consider natural hazards as possible triggers. As already noted in this study, the triggering of a technological disaster, including Natech, can lead to significant negative impacts not only in the vicinity of the incident, but more broadly by propagating disruptions to different sectors.

The Water Framework Directive (Directive 2000/60/EC) requires *EU Member States* to protect water resources including "mitigating the effects of floods and droughts" by specifically taking action "to prevent significant losses of pollutants from technical installations, and to prevent and/or to reduce the impact of accidental pollution incidents for example as a result of floods". On the other hand, the Floods Directive (Directive 2007/60/EC) requires *EU Member States* to undertake risk analyses and increase the protection against floods.

Additionally, the *Action Plan on the Sendai Framework for Disaster Risk Reduction 2015-2030* (EC, 2016a) proposes to enhance disaster risk management and resilience, and their integration in EU policies, including those on climate change. In particular, the new *EU Strategy on Adaptation to Climate Change* (EC, 2021b), where *EU Member States* are required to develop climate change adaptation strategies and plans, informed by accessible and robust risk assessments, to adjust their socioeconomic systems to climate change in order to reduce climate-related risk, mitigate negative impacts and build resilience.

Following this policy overview, a few critical points have been identified in terms of governance:

- **While indirectly the negative impacts on EU security and defence are somewhat addressed by current policy acts, there is no tangible scope or mandate for their application in that context**, in fact some of the policy acts clearly exclude the military (e.g., Seveso-III Directive). It is unclear if national policies and international standards (e.g., *European Defence Standards Reference System* [EDSTAR] ([84]), *International Organization for Standardization* [ISO], *NATO Standardization Agreement* [STANAG],) are effectivly bridging the

([84]) EDA. European Defence Standards Reference System (EDSTAR) (accessed 1 July 2021) https://edstar.eda.europa.eu/

gap of EU policy acts and providing the tools to further enhance the resilience of military installations and defence critical infrastructure, to work towards climate neutrality (*Regulation (EU) 2021/1119*) and environmental sustainability;

- **Operators of critical infrastructure** (e.g. power grid) **know very little about the business of infrastructure they depend upon** (e.g., telecommunications) **and exert little to no control over them.** The same reasoning applies to military installations that depend on utilities (e.g., water and energy) to effectively fulfil their mission;
- While a EU Wildfire Directive, similar to the Floods Directive, does currently not exist, the EU has recently adopted a EU Forest Strategy (EC, 2021a). As wildfires represent the most common natural hazard in Europe (Figure 2), improved national and EU-level governance on land-use planning in Wildland-Urban and Wildland-Industrial Interface regions is needed (Kern and Krausmann, 2020) and might reduce the risk to military installations, but also military activities (e.g. training);
- **Absence of dedicated entities/programs** (e.g., *DOD Environmental Research and Development Programme* [SERDP], *NATO Science for Peace and Security Programme* [SPS]) **at the EU level tasked with R&D&I and knowledge management** and support to the EU MODs (e.g., risk management, incident data collection and reporting, tool development and standardization) regarding the impacts of natural hazards and climate change on military installations and defence critical infrastructure. However, the *European Defence Agency* (EDA) has been taking steps in this regard ([85]).

7.1.2 Knowledge

A successful implementation of measures to reduce risk and build resilience to the impacts of natural hazards and climate change requires a good understanding not only of the physical processes, but also of the vulnerability of exposed communities, infrastructure and ecosystems, and their capacity to cope with, adapt to and recover quickly from impacts. Scientific knowledge, and its management, is key as it enables stakeholders to learn lessons from past disasters, assess current and future risk, and develop and implement cost-effective solutions to reduce risk and build resilience. In this respect a few points have been identified:

- **The link between some natural hazards and climate change** (e.g., storms) **is still unclear**, constraining risk projections, the provision of evidence for improved decision making and the design and implementation of solutions that account for the non-stationarity of climate-related natural hazards;
- Natural hazards such as landslides, rainfall-induced flash floods, drought, compound events, but also NAtech accidents, are often underreported, limiting the development of a better understanding about events – a basic step towards reducing risk and building resilience;
- **Paucity of (open) literature** (e.g., handbooks, technical reports, scientific papers) **and data about the direct and indirect impacts of natural hazards and climate change on military installations and defence critical infrastructure in Europe**, the exposure and vulnerability of facilities, equipment and components makes it hard to have an accurate picture of risk. **A step towards bridging this gap is the ongoing EDA-JRC joint study on the impacts of climate change on defence-related critical energy infrastructure in the context of the CF SEDSS**;
- **The reliable collection, management and sharing of good quality data with appropriate coverage** (e.g., monitoring networks, post-event surveys) is dependent on the changing priorities and policies of each *EU Member State*. Given the importance of observations to improve numerical models (data assimilation and validation) and given that impacts of natural hazards and climate change are often transboundary and of collective interest, EU-level action in this regard could be beneficial;

([85]) EDA. Energy and Environment (EnE) Programme (https://eda.europa.eu/what-we-do/all-activities/activities-search/energy-and-environment-programme) and Consultation Forum for Sustainable Energy in the Defence and Security Sector (CF SEDSS) (https://eda.europa.eu/what-we-do/eu-policies/consultation-forum) (accessed 1 July 2021).

- Although significant progress has been made in reporting power outages with the launch of the *ENTSO-E Transparency Platform* in 2015 ([86]), forced power outages do not specify the exact cause of disruption or failure (e.g., flood, strong wind). This information is essential to better understand the indirect impacts of natural hazards and climate change on military installations;

- Data on the disruption and failure of other cross-sector dependencies, such as fuel and water supply would be also important, but does not seem to be easily accessible;

- **Knowledge about the security implications of natural hazards and climate change** (e.g., conflict forecast, threat- and burden-multiplication) **seems incomplete.** For example, although the Global Conflict Risk Index has been an important step to bridge this gap, it still does not account for natural hazards and climate change (e.g., De Groeve et al., 2014; Halkia et al., 2020). Furthermore, conflict forecast and early warning may require other approaches such as system dynamics and agent-based modelling (e.g., BenDor and Scheffran, 2019);

- **Risk reduction and resilience may entail significant trade-offs in terms of climate neutrality and environmental sustainability**, something that is not well understood yet.

7.1.3 Methods

Comprehensive and detailed risk assessments are an essential first step to reduce risk and build resilience to natural hazards and climate change, including at military installations. They provide the technical basis to support decision-making regarding the development and implementation of measures and prioritization of investments in prevention, preparedness, response and recovery. Risk assessment is key in technological risk reduction, is also acknowledged in the UCPM, and is well supported by guidelines (EC, 2015, 2019b) and standards (e.g., ISO 31000). Although progress in the preparation and submission of NRAs has been significant (Poljanšek et al., 2021), a few gaps have been identified:

- **Risk assessments tend to focus on individual hazards, structures and regions.** They are often produced assuming stationarity, failing to account for future changes in climate-related natural hazards, and they often fail to account for compound events and whole systems, potentially neglecting important indirect negative impacts and transboundary and spillover effects;

- **Damage curves specific to each natural hazard and for different damage states of infrastructure and their specific components are not widely available, complete and consistent** between sources. They often focus on a single load parameter (e.g., Table 1) when others may be relevant too (Ward et al., 2020). This limits the possibility for a more accurate representation of risk and potential consequences of technological accidents;

- **Paucity of resilience and consequence analysis of natural hazards and climate change**;

- **Delay in the adoption of adaptive planning** (e.g., contingency and business continuity) **and management specific to each military installation and defence critical infrastructure.** This is essential as impacts of climate-related natural hazards may change regionally;

- **Paucity of stress tests** (e.g., power outages) **and crisis gaming** (including scenario analysis and table top exercises on catastrophic and black swan events) with a focus on natural hazards and climate change. This would be an essential step towards robust decision making in a context of uncertainty and complexity of future threats to military installations and operations;

- Separate, but similar, frameworks such as risk reduction, climate change adaptation, critical infrastructure protection and resilience, may create unnecessary confusion and duplicate efforts while wasting resources. They also lack scope for military installations and defence critical infrastructure.

7.1.4 Tools

Decision-making aided by advanced tools has become common and vital in today's risk management landscape. The increased complexity of infrastructure and systems, a desire to continually reduce uncertainty, account for the optimization of multiple outcomes and resources, while at the same time ensure compliance,

([86]) ENTSO-E. Transparency Platform (accessed 1 July 2021). https://transparency.entsoe.eu require sophisticated tools that can handle a significant number of operations and data in an efficient way. Although tools have evolved significantly, closely following an increase in computational power, a few gaps have been identified:

- Paucity of models for convective storms that consider sub-perils (e.g., hail, wind gusts, tornados, heavy rain and lightning) and possible changes with global warming (Ward et al., 2020);
- Inconsistencies in regional load maps used in design and building standards (Sousa et al., 2019);
- Possible need for regionally consistent guidelines and standards (e.g., building codes, installation master planning), specific to the military that account for natural hazards and climate change;
- **Paucity of tools that can handle the complexity of system-wide risk assessments for multiple natural hazards and climate change**, including compound events, and cascading effects;
- **Paucity of forecast and early warning for brownouts and blackouts to military installations**;
- Paucity of tools to assess resilience of military installations and defence critical infrastructure;
- **Paucity of tools to analyse trade-offs between the implementation of risk reduction and resilience measures, climate neutrality, environmental sustainability, operational effectiveness and cost** ([87]);
- Given the high number of numerical models (e.g., hydrodynamic), a pre-determined set of requirments and validation framework could aid in their election and enhance trustworthiness.

7.1.5 Practices

In order to effectively reduce risk and increase resilience to natural hazards and climate change it is necessary that the military adopt a number of best practices that are already common in some sectors. In this regard a few shortcomings have been identified:

- Possibly **too much focus on reactive approaches, rather than proactive, to disaster risk**;
- Possibly **not enough integration, in military planning and investment cycles, of risk assessment** of military installations and assets **that accounts for all hazards**, including compound events;
- Possible need to strengthen the systems approach to risk management, considering cross-sector dependencies and cascading effects;
- Possible **need to strengthen collaboration and effective coordination across military departments and jurisdictions** (e.g., cross-border) to strengthen resilience, identify (and prioritize) measures, bring down barriers to implementation, learn lessons, and share best practices;
- Possible **need to strengthen participatory approaches (cross-sector, whole community, civil-military cooperation)** to find mutually accepted solutions and modes of implementation, increase transparency, transfer knowledge, avoid duplication of efforts, optimize resource use, raise awareness and build capacity;
- Provisions to train personnel to repond to disasters, which could be exacerbated by climate change, are possibly not in place;
- **Natural hazards, climate change, and the weaponization of the environment are not explicitly addressed in the framework for countering hybrid threats.**

([87]) Baxter, J. (2018). Federal Utility Partnership Working Group Seminar. DOD https://www.energy.gov/sites/default/files/2018/04/f51/fupwg_spring_2018_20-baxter.pdf

7.2 Recommendations

Since the *Paper from the High Representative and the European Commission to the European Council*, S113/08, that framed climate change as a threat multiplier, commitments to include climate change in EU security and defence policy have increased. The most significant development to date being the *EU Climate Change and Defence Roadmap* (EEAS, 2020) that aims at better understanding the negative impacts of climate change and accounting for climate change in CSDP missions and operations, ensuring their future effectiveness. In line with the *European Green Deal* (EC, 2019a), that aims at carbon neutrality (*Regulation (EU) 2021/1119*), resilience and environmental sustainability in the EU by 2050, the *EU Climate Change and Defence Roadmap* also aims at making European defence more energy efficient, cutting carbon emissions, and more independent from external suppliers. Table 19 summarizes the proposed actions in the *EU Climate Change and Defence Roadmap*.

Table 19. Short-, medium-, and long-term actions to build resilience according to the *EU Climate Change and Defence Roadmap* (EEAS, 2020).

Operational	Situational awareness and understanding;
	Integrated early warning and forecast systems, climate models, conflict analysis, capability, missions and operations;
	Strategic foresights;
	Operational guidelines and standard operating procedures;
	Data collection and best practices in missions and operations;
	Knowledge sharing;
	Military land conservation.
Capability planning and development	Training, exercises, education and participation in existing programmes;
	Scenario and strategic planning;
	Monitor the implementation of measures (e.g., procurement, infrastructure, awareness and commitment);
	European defence infrastructure impact assessment;
	Resilience study of critical energy infrastructure to hybrid threats;
	Establish climate-related objectives for the Permanent Structured Cooperation (PESCO).
Multilateralism and partnerships	Address climate change and environmental aspects related to security;
	UN and NATO missions and operations;
	Include climate-related security threats, climate change adaptation and mitigation in EU defence and CSDP.

From this analysis, a few points immediately emerge:

- As policy becomes ever more complex, fragmented, and somewhat redundant, effective compliance and negotiations may become increasingly challenging;
- It is clear that **managing risk associated to natural hazards and climate change requires collective action**, the engagement of whole communities and sectors (including civil-military cooperation) due to increasing digitalization and deepening dependencies, strengthened solidarity within the EU and international cooperation for development as a warranty for EU security;
- **Commitments to account for climate change in CSDP missions and operations are a very significant step, but real progress is unclear (or uncommunicated)**, including beyond the CSDP. Failing to progress in this context may not only jeopardize effective EU security and defence, irrespective of future changes in the risk landscape, but also affect the achievement of EU goals of carbon neutrality, resilience and environmental sustainability, as the military in Europe hold a non-negligible share of emissions and land property.

EU Member States should take advantage of the impetus given by the most recent policy acts, in particular the *European Green Deal* (EC, 2019a) and the *EU Climate Change and Defence Roadmap* (EEAS, 2020), to overcome remaining barriers and quickly move forward in ways that serve both resilience, carbon neutrality and environmental sustainability, while safeguarding operational effectiveness.

In Table 20, a list of actions to build resilience to natural hazards and climate change in EU defence are proposed. This list is non-exhaustive and complementary to the one proposed by the *EU Climate Change and Defence Roadmap* (EC, 2020), summarized in Table 19. Recommendations were devised with the view to help the EU MODs, the military and any other relevant stakeholders, pick up momentum in their path towards resilience, carbon neutrality and environmental sustainability.

Table 20. Short-, medium-, and long-term actions to build resilience to natural hazards and climate change in EU defence, in addition to those proposed in the *EU Climate Change and Defence Roadmap* (EEAS, 2020).

Short-term actions	Define EU defence critical infrastructure (e.g. European Energy Security Strategy [EC, 2014]) based on mission assurance;
	The selection of GHG emission scenarios should follow a technical recommendation based on best available science and should be regionally consistent;
	Develop a pilot study to understand current risk management in practice: • Produce all-hazard risk assessments for baseline conditions and projected changes using a systems approach, considering potential cascading effects; • Produce a portfolio of measures (structural, non-structural and nature-based), ranked based on cost-effectiveness (including win-win, no-regret, reversible, flexible, safety margin and reduced time horizon solutions) and feasibility (e.g. ownership, regulation, context, impacts); • Document needs, barriers and opportunities, including the potential for cross-fertilization; • Produce recommendations to advance risk reduction and resilience building at the EU-level.
	Further investigate the impacts of natural hazards and climate change on defence critical infrastructure and EU security, particularly on defence-related critical energy infrastructure. An example is the ongoing EDA-JRC joint study in the context of the CF SEDSS;
	Develop scenarios for crisis gaming, especially considering high uncertainty cases (e.g., black swans);
	Define a long-term strategy, guided by key principles (e.g., solidarity, subsidiarity, complementarity, confidentiality, cooperation, proportionality), to support risk reduction and resilience building of military installations and defence critical infrastructure in Europe, mitigating potential losses and disruptions;
	Engage EU defence in carbon neutrality, resilience and environmental sustainability.
Medium-term actions	Establish a permanent program to advance R&D&I on the various dimensions of climate change, from managing risks against and building resilience to natural hazards and climate change, carbon neutrality and environmental sustainability: • Supporting the integration of risk management of natural hazards and climate change in military planning and investment lifecycles; • Interfacing with the EU MODs, other relevant stakeholders and multinational programmes to facilitate civilian-military cooperation under a system-wide and whole community approach; • Reporting on the threats of natural hazards and climate change to EU security and defence; • Supporting the development of dedicated guidelines and standards for EU defence (e.g., *DOD Unified Facilities Criteria*); • Supporting the definition of resilience, carbon neutrality and environmental sustainability targets/goals in EU defence and the monitoring of progress through performance metrics; • Supporting the development and implementation of new tools, methodologies and technologies; • Supporting the definition of acceptable risk and risk profiles for EU defence (risk thresholds); • Supporting the prioritization of measures in relation to other civilian critical infrastructure, weighing in mission assurance, cost-effectiveness and feasibility; • Supporting the development of scenarios for crisis gaming and convening exercises, workshops and training; • Establishing task force groups with rapid response funds to conduct surveys, systematically collect, assemble and analyse perishable post-event data, produce discussions and periodically broadcast findings; • Integrating natural hazards and climate change in conflict forecast to map and warn of possible future security implications, including new pathways for hybrid threats (e.g., Meyer et al, 2021).
	Address the transition in defence energy and related aspects such as environmental.

Table 21. (continuation).

Long-term actions	Effectively reduce the environmental footprint of EU defence (e.g., circular economy, green procurement, dual-use technology), which has the additional advantages of reducing resource dependency, increasing resource efficiency, minimizing waste and producing cost savings, stimulating innovation, driving market transition and raising awareness;
	Transition as much as possible to low-carbon military activities (e.g., smart micro-grids using hybrid power sources and storage, renewable energy, energy efficiency, vehicle–to-grid, clean transport, biofuel, hydrogen), whenever it does not compromise operational effectiveness.

8 Conclusion

The present study has analysed the impacts of natural hazards and climate change on EU security and defence. It identifies gaps and provides a set of preliminary recommendations that may help the military in the path towards resilience against climate change and natural hazard impacts, carbon neutrality and environmental sustainability.

Europe faces a number of defence and security threats, natural hazards and climate change will exacerbate them by modifying the conditions in which the military operate, adding uncertainty, adversity and complexity. This will probably shift the way the military organize, but also the type of missions, their frequency of deployment, implementation, operational conditions and theatres of operations. Factors that may contribute with additional burden, that may stretch budgets, shift attention and impact military capability. Essentially, it should shift the way the military think.

Initiatives to understand the implications of natural hazards and climate change have already been launched in Europe, and the *EU Climate Change and Defence Roadmap* is a case in point. However, it is still unclear if in practice there is enough awareness, capacity and if the current pace in the adoption of measures is in line with resilience building and the target to reduce 55% of GHG emissions by 2030. The next few years are absolutely decisive.

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Terminology

Climate change	A change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods (UNFCCC, 1992).
Climate change adaptation	Actions to prepare for and adjust to current and future effects of climate change ([88]).
Climate change mitigation	Actions to reduce the concentration of carbon dioxide in the atmosphere ([89]).
Climate neutrality	When the amount of greenhouse gases emitted to the atmosphere are the same as the amount of greenhouse gases removed from the atmosphere by different sinks such as vegetation and the oceans (i. e., net-zero greenhouse gas emissions).
Climate refugee	Persons displaced in the context of disasters and climate change ([90]).
Contingency basing	Process of planning, establishing, constructing, operating, managing, transferring and transitioning or closing a non-enduring location supporting a military command (JCS, 2019).
Disaster	A serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources (UNDRR, 2009). Any situation which has or may have a severe impact on people, the environment, or property, including cultural heritage (Decision No 1313/2013/EU).
Environmental sustainability	Meeting the needs of the present without compromising the ability of future generations to meet their own needs (UN, 1987).
Exposure	People, property, systems, or other elements present in hazard zones that are thereby subject to potential losses (UNDRR, 2009).
Facility	Any property consisting of one or more of the following: building, structure, utility system, pavement, and underlying land (DOD, 2021a).
Force structure	The operational availability and organization of military personnel, weapons and equipment. It can be characterized by in-place forces, deployable forces at different levels of readiness and low readiness forces used for large-scale defence ([91]).
Lifelines	Are those essential utility and transportation systems that serve communities across all jurisdictions and locales ([92]).
Military asset	Any resource owned and controlled by the military for operational purposes (e.g., personnel, equipment, electronics, aircrafts, tactical vehicles, ships, and weapons) ([93]).
Military capability	The ability to effectively deter, defend, support and ensure stability and peace under specific conditions. It can be sub-divide into force structure, modernization, operational readiness and sustainment (JCS, 2001).

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(93) North Atlantic Treaty Organization. NATOTerm – The Official Terminology Database (accessed 1 July 2021). https://nso.nato.int/natoterm/Web.mvc

Military installation	Military base or location from which operations are projected and/or supported (DOD, 2021a).
Mission assurance	Process to protect or ensure the continued function and resilience of capabilities and assets, including personnel, equipment, facilities, networks, information and information systems, infrastructure, and supply chains, critical to the execution of Department of Defence mission-essential functions (DOD, 2021a).
Natural hazard	Natural process or phenomenon that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption or environmental damage (UNDRR, 2009).
Nature-based solutions	Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions ([94]).
Non-structural measures	Non-structural measures are measures not involving physical construction which use knowledge, practice or agreement to reduce disaster risk and impacts ([95]).
Operational readiness	Capability of a unit/formation, weapons system, or equipment to perform at a precise moment a mission or function, for which it was organized or designed for (DOD, 2021a).
Resilience	The ability not only to withstand and cope with challenges but also to transform in a sustainable, fair, and democratic manner (EC, 2020b).
	The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions (UNDRR, 2009).
Risk	The combination of the probability of an event and its negative consequences (UNDRR, 2009).
Structural measures	Structural measures are any physical construction to reduce or avoid possible impacts of hazards, or the application of engineering techniques or technology to achieve resilience ([95]).
Sustainment	Provision of logistics and personnel services required to maintain and prolong operations until successful mission accomplishment (DOD, 2021a).
Vulnerability	The characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard (UNDRR, 2009).
Weapons system	A combination of one or more weapons with all related equipment, materials, services, personnel, and means of delivery and deployment required for self-sufficiency (JCS, 2001).

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