Deliverable 1.1

Report on the most relevant methodologies and technologies for enhancing the response capacity to geo and weather events

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Executive summary

This deliverable offers a comprehensive overview of the state-of-the-art of forecasting systems for Weather and Geo events used by a variety of end users, from the public to civil protection. Relying on the experience and expertise of **GOBEYOND** partners.

It points to the advantages, weaknesses and potential evolution of the warning systems, both from the pure hazard to the risk. Several systems are described in detail; however, the overview does not set out to be a comprehensive review of existing systems. It is rather using examples of systems to highlight typical features for the specific hazard.

The overview also attempts to connect the warning systems for weather and geo hazards to see where the gaps are that can be overcome to bring the two disciplines closer and potentially provide a combined system, as the **GOBEYOND** project aims. There are differences in terms of spatial scale, technical readiness and end-user groups, but the biggest difference by far is in the temporal scale. Geo hazards have very sophisticated systems that can provide information once a hazard has occurred, whereas weather hazards provide this information well before the event is predicted. This difference is from the fact that geo-hazards are inherently difficult to predict in time. However, combined systems still would provide important information, especially for the increased impact of combined events. Further, synergies from sharing exposure and vulnerability data are an added benefit from combining geo and weather risks into a hybrid risk forecasting system.

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List of acronyms and abbreviations

ACA	Water Agency of Catalonia
ACC	Aviation Colour Code
AI	Artificial intelligence
API	Application programming interface
BoM	Australian Bureau of Meteorology
CAP	Common Alerting Protocol
CEA	French Commissariat à l’Energie Atomique
CEMS	Copernicus Emergency Management Service
CII	Climate Impact Indicators
COA	Advanced Operational Centre
DART	Deep-ocean Assessment and Reporting of Tsunamis
DEM	Digital elevation model
DPC	Italian civil protection agency
DWD	German meteorological office
EASE	Earthquake AShfall Evaluation
ECMWF	European Centre for Medium-Range Weather Forecast
EDO	European drought observatory
EEW	Earthquake Early Warning
EFAS	European flood awareness system
EFFIS	European Fire Forecast Information System
EFI	Extreme forecast index
EHF	Excess heat factor
ELER	Earthquake Loss Estimation Routine
ERCC	Emergency Response Coordination Centre
ETS	equitable threat score
EUMETNET	European National Meteorological Services
EWS	Early warning systems
EPIC	European Precipitation Index based on Climatology
ESA	European space agency
FF	Flash floods
FFG	Flash Flood guidance
fPAR	Fraction of absorbed photosynthetic active radiation
FTP	File Transfer Protocol
FWI	Fire weather index
GFZ	Geoforschungszentrum
GIS	Geographic Information System
GloFAS	Global flood awareness system
GMPE	Ground motion prediction equations
GMICE	Ground-Motion-Intensity Conversion Equation
GWIS	Global Wildfire Information System
IAVW	International Airways Volcano Watch
ICG	Intergovernmental Coordination Groups
ICGC	Cartographic and Geological Institute of Catalonia
ID	Intensity-Duration

IEWS	Impact based early warning systems
ISNet	Irpinia Seismic Network
IMO	Icelandic Meteorological Office
INGV	National Institute of Geophysics and Volcanology
IOC	Intergovernmental Oceanographic Commission of the UNESCO
JRC	European Commission’s Joint Research Centre
LAI	Leaf area index
LEWS	Landslide early warning systems
LT	Lead time
MCMCs	Monte-Carlo Markov Chains
MET	Norwegian Meteorological Institute
ML	Machine learning
MODIS	Moderate Resolution Imaging Spectroradiometer
MWO	Meteorological Watch Office
NASA	US National Aeronautics and Space Administration
NEAMTWS	North-eastern Atlantic, the Mediterranean and connected seas
NHMS	National hydrological or meteorological services
NOAA	US National Oceanic and Atmospheric Administration
NPRA	Norwegian Public Road Administration
NRC	Natural Resources Canada
NTR	Non-tidal residuals
NTWC	National Tsunami Warning Centers
NVE	The Norwegian Water Resources and Energy Directorate
NWP	Numerical weather prediction models
OGC	Open geospatial consortium
OPERA	Operational Programme for the Exchange of Weather Radar Information
QPE	Quantitative precipitation estimates
QPE	Quantitative precipitation forecasts
P wave	Primary wave
PAGER	Prompt Assessment of Global Earthquakes for Response
Pd	Peak of displacement
Pa	Peak of acceleration
Pv	Peak of velocity
PGA	Peak ground acceleration
PGV	Peak ground velocity
PTW	P-wave time window
S wave	Secondary wave
S2S	Sub-seasonal to seasonal
SAVE	on-Site Alert level
SHOM	French Hydrographic and Oceanographic Service
SiAM	Italian national warning system for seismic sources
SIGE	Information System for Emergency Management
SMC	Catalonia Meteorological Service
SPI	Standardised precipitation index
TSP	Tsunami Service Provider

TTT	Tsunami Travel Times
TWFP	Tsunami Focal Warning Points
UAVs	Unmanned aerial vehicles
UCPM	EU Union Civil Protection Mechanism
UHI	Urban heat island
UNINA	University of Naples
USGS	U.S. Geological Survey
VAA	Volcanic Ash Advisories
VAACs	Volcanic Ash Advisory Centers
VAG	Volcanic Ash Graphics
VOD	Vegetation optical depth
VONA	Volcano Observatory Notice to Aviation
WMO	World Meteorological Organisation
WFS	Web feature service
WMS	Web map service

1. Introduction

The impact of natural hazards affects all parts of the world, and forecasting and early warning systems (EWS) are important tools to mitigate the effect on lives, properties and livelihood (Merz et al., 2020). However, the existing systems that provide forecasts of hazards, they do not usually provide information on the impact of these hazards on society in terms of damage.

Forecast and warning have focused on physical event characteristics, such as magnitude, spatial extent, and duration of the impending event. Recently, the provision of information on the potential event impacts, such as number and location of affected people, damage to buildings and infrastructure, or disruption of services, has gained attention. The definition of impact forecast is to consider what elements are at risk of damage from a specific hazard. To account to for this, the exposure, or the affected elements such as population or infrastructure as well as their vulnerability to damage needs to be assessed. It is also important to consider the uncertainty of the forecast, since the probabilistic forecasts has shown to give better guidance to users than deterministic forecasts (Fundel et al., 2019). The concept of impact of forecasts combined with likelihood of the event to create a risk matrix to guide when action is needed (Figure 1). These systems aim to provide timely and accurate information about impending hazards, enabling communities to take proactive measures to reduce risks and minimize the impact on lives, infrastructure, and economies.

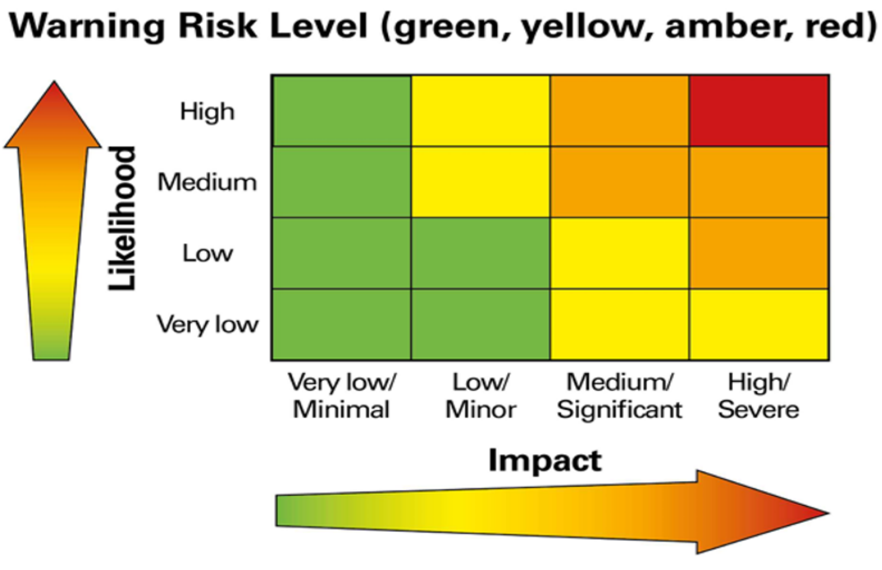


Figure 1 Risk matrix where the impact of a specific event is weighted against the likelihood to guide when actions are needed.

The EU project **GOBEYOND** aims at the development of a common and shared framework for Multi-risk Impact-based EWS (MR-IEWS) of geological and weather-related natural hazards. The considered geological hazards include earthquakes, volcanic eruptions, tsunamis and landslide, while the analysed weather hazards comprise floods, flash floods, windstorms, storm surges, heat waves, drought and forest fires.

The type of forecast systems available differs dramatically in terms of time of the alert before or after the event occurrence, the spatial extent of the alerted region, the lead time (e.g. the time available for emergency safety actions before the event disastrous effects) as well as the level of maturity of the operational systems (Figure 2). Depending on the rapidity of the event detection and alert issuance, the lead times can differ from seconds (earthquakes) to months (droughts), and spatial scales from a couple of hundreds of meters to thousands of kilometres.

Forecasting, early warning systems and rapid disaster risk information are fundamental of disaster risk reduction (UNDRR, 2019). The Sendai Framework for Disaster Risk Reduction calls for a substantial increase in the availability of multi-hazard early warning systems and rapid disaster risk information by 2030 (WHO, 2015). This comprehensive approach ensures that communities are prepared for a range of potential disasters, occurring isolated or in a cascade triggering mechanism. A typical example is the seismic and ground instability risks in volcanic areas, related to pre-eruptive physical processes accompanying the rise of the magma to the surface.

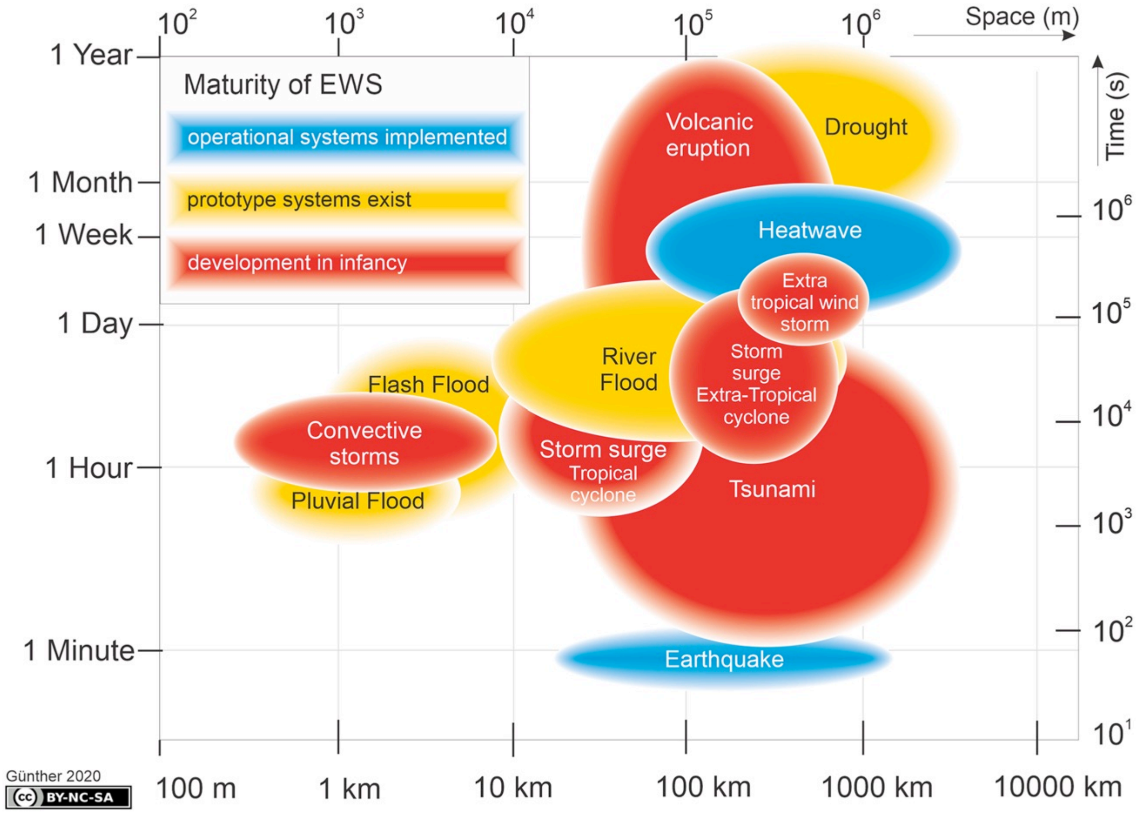


Figure 2 Temporal and spatial scales for a number impact-based forecasts and an assessment the maturity of existing forecast systems

Source: Merz et al., 2020

Multi-hazard early warning systems rely on robust risk assessment methodologies and continuous monitoring of geological and meteorological conditions. Advanced technologies such as remote sensing, satellite imagery, weather radar, dense networks of seismometers, and ground sensors are utilized to detect precursors (in case of volcanoes and landslides) or record in real-time the source radiated waves (earthquakes, tsunamis) to monitor changes in hazard parameters or predict the hazard impact through a refined source characterization and propagation modelling.

Early warning systems typically establish thresholds and triggers based on models, scientific data and observations, whereas available, historical patterns to determine when warnings should be issued. For example, certain rainfall thresholds may trigger flood warnings, while seismic activity in a volcanic area above a certain magnitude may prompt earthquake alerts. Threshold based earthquake early warning systems prompt an alarm when the predicted level of ground shaking can exceed a user-set threshold of not tolerated severe damage.

Timely and effective communication is essential for ensuring that warnings reach the affected communities promptly. Early warning systems employ various communication channels, including traditional media, mobile phones, sirens, social media, and community networks, to disseminate warnings in a clear and understandable manner. These tools and their efficiency in providing reliable warning to communities will be investigated and review in deliverable D1.2.

The relevance and novelty of impact-based early warning systems rely in providing warnings that are tailored to the specific needs and vulnerabilities of different communities. This may include considerations such as local infrastructure, population density, socio-economic factors, and cultural practices. In this aspect, engaging local communities and their emergency managing authorities in the development and implementation of early warning systems enhances their effectiveness and ensures that warnings are relevant and actionable. Community participation fosters a sense of ownership and encourages proactive preparedness measures.

One primary issue that goes beyond the scientific and technological development is the building of local capacity for disaster preparedness and response that is another fundamental component of IEWS. This involves training community members, emergency responders, government officials, and other stakeholders in hazard awareness, evacuation procedures, first aid, and other relevant skills. Since EWS are dynamic systems that evolve over time, their update should be continuous in time and based on lessons learned from past events, advances in technology, and changes in risk profiles. Continuous evaluation, feedback mechanisms, and innovation are critical for enhancing the effectiveness and resilience of early warning systems.

This deliverable aims at collecting a comprehensive review of the state-of-the-art on methodologies and technologies implemented in current weather and geo hazard early warning systems, that are primary based on the event impact estimation.

For each methodology description we follow a common general structure that includes state-of-the-art and objectives, principles and element of theory, technological requirements, existence of operating platforms for alert visualization and issuance, protocols for alert dissemination or management agencies, examples of validation as from literature, real-time and/or offline actual use, end-users and stakeholders, *Pros* and *cons* of the methodologies.

Section 2 describes early warning methods applied to weather hazards, while EWS for Geohazards are described in section 3. Finally, section 4 provides a comparative analysis and perspective of integration of weather and geohazards.

2. Methodologies and technologies for enhancing response capacity in Weather events

The weather hazards that are described in this section are floods, flash floods, windstorms, storm surges, heat waves, drought, and forest fires. For each risk the level of maturity is explored, and a way forward to implement risk methodologies is discussed if feasible.

2.1. Flood forecasts

2.1.1. State-of-the-art and objectives

Flooding is one of the of most damaging natural hazards in terms of lives and loss of property world-wide today, and its effects is likely to be exacerbated with future climate change (Wing et al., 2022). Floodings are caused by a number of factors, where the most important are intense or long-lasting rainfall, snowmelt or coastal surges. This chapter will deal with floods caused by overflowing riverbanks, snow melt and groundwater-induced flooding. Flash floods caused by intense precipitation is dealt with in chapter 2.2 and storm surge flooding in chapter 2.4. Operational flood forecasting for warning is today in most cases done using a rainfall-runoff model forced by numerical weather prediction models (NWP), and most often ensemble forecasts are being used (Cloke & Pappenberger, 2009; Pappenberger et al., 2016). The output river discharge is sometimes re-calculated into flood extent, but often is the discharge taken as proxy for flood risk.

Different modelling approaches are used for operational forecasts, which can be broadly categorised into very detailed physics-based (distributed) to simpler lumped (conceptual) model where some parametrisations are described through statistical relationships (Maidment, 1992). Pure black-box models also exist, and these models have become popular again thanks to the rise of machine learning methods in recent years. The different type of models can also be differentiated by their treatment of the catchment area: lumped models consider the catchment as a single unit, while distributed models implicitly account for spatial differences in the catchment. Operational flood forecasting uses real-time observations and satellite data for near-immediate flood detection and modelling, accelerating emergency responses.

Historically, flood engineering was done through pure statistical models, using historical data of discharge and flood events to calculate flood return periods of major events. The weakness of these methods is skewness of the distribution of events which makes the modelling of extreme events uncertain. The current state-of-the-art of flood forecasting is built on more than 50 years of numerical modelling, leading to today's web-based automated system for flood forecasts (Wu et al., 2020). Recently, there has been a notable increase in the exploration of artificial intelligence (AI) for flood forecasting (Nevo et al., 2022). The methods that use machine learning (ML) algorithms trained on vast historical data such as rainfall, river flow, and satellite imagery.

2.1.2. Principles and elements of theory

The basic principle of hydrological modelling is solving the water balance (or budget) equation, which can be expressed as:

$$P = Q + ET + \frac{dS}{dt}$$

where P is precipitation, Q is runoff, ET is evapotranspiration and dS/dt is the change in the water storage. The water balance can be implemented in smaller gridded parts of the landscape, or over larger water elements (water sheds). The outlet point of a watershed is defined as the point to where all water that falls within the catchment will be flowing through unless it is evaporated or stored. The runoff in a watershed or a grid space is then translated into discharge through a transfer function, which can be a simplified delay function or complex hydraulic models using for example kinematic wave functions. The final step is to then translate the discharge into a flood extent, using a two- or three-dimensional flood inundation model, as exemplified with the LISFLOOD hydrological model used in the European (EFAS) and Global (GloFAS) Flood Awareness System in Figure 3 (Burek et al., 2013; JRC, 2020).

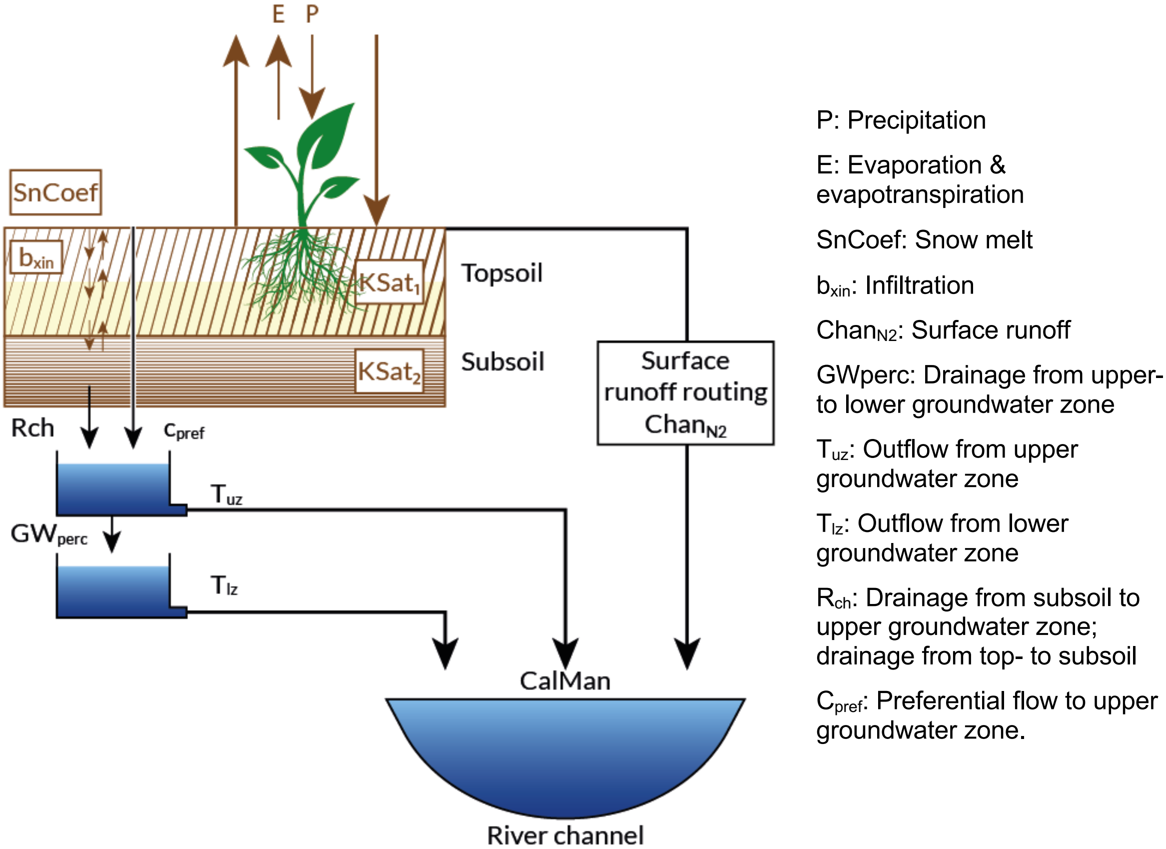


Figure 3 Overview of the LISFLOOD model

Operational flood forecasting exists all over the world in either local, regional or national continental or global implementations, and more and more commonly ensemble forecasts are being used (Pappenberger et al., 2016). The ensemble information is either displayed as is with probabilities or transformed into deterministic information in decision support systems as EFAS. The lead time of flood forecasts ranges from hours to weeks depending on the system. Early warning systems as the EFAS have typically a lead time from a few hours of up to 15 days, but there are also systems that give information on sub-seasonal to seasonal (S2S) time scales, ranging from weeks to months (Wetterhall & Di Giuseppe, 2018; White et al., 2022).

2.1.3. Technological requirements

Flood real-time forecasting relies on forecasts and observations of the forcing variables - typically temperature and precipitation – being available in real time. Also, other variables, such as soil moisture, snow and hydrological measurements can be used in real-time to update the model state. The observations are either collected from observation stations, derived from remote sensing or modelled through NWP models. The model is then forced by forecast to produce a forecast from hours up to weeks or even months. The spatial scale of hydrological models is depending on the application and type of model, but the typical scale id from a few km^2 up to the full catchment, which can be several thousand km^2. The operational hydrological models are implemented in automated systems which are monitored 24/7.

2.1.4. Operational platforms for alert visualization and dissemination

There are a number of existing platforms for hydrological forecasts on regional and national level (Pappenberger et al., 2016). The already mentioned EFAS system is a good example of an operational platform where the forecasts of a number of variables are visualised and notifications of flood events are issued to the end users, including information from the national flood notification systems. EFAS also provides impact forecasts, where the flood forecasts (hazards) are combined with exposure and vulnerability data to provide an early impact assessment Figure 4.

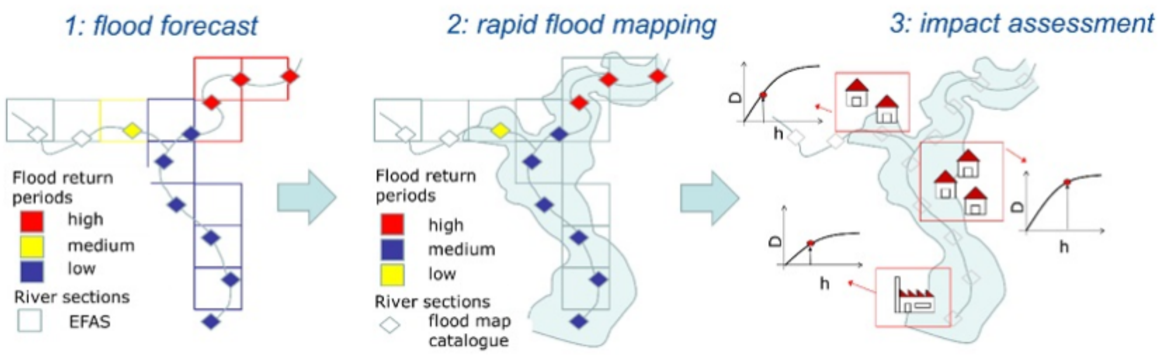


Figure 4 Rapid risk assessment in EFAS using information on hazard, vulnerability and exposure.

In the example of EFAS, the notifications of upcoming events are sent out as email alerts to the local authorities, not to the public. This, to ensure the “One voice” principle when it comes to issuing public warnings. The development of the flood event can then be monitored through the EFAS web page. It should be mentioned that the flood forecasts are for the hazard and not the impact.

2.1.5. Validation

Hydrological models are validated, both in the calibration, or training, process and in the operational context (Alfieri et al., 2014). The hydrological model output and forecasts can be validated against observations or modelled output, either using probabilistic scores such as the Brier score (Brier, 1950) and the continuous ranked probability score (Hersbach, 2000). or classical error characteristics of time series analysis. A very widely used metric for assessing hydrological time series is the Kling-Gupta efficiency (Gupta &

Kling, 2011) which is a goodness-of-fit measure of a simulation against observations at a specific point.

2.1.6. End users

The end users of flood forecasts are firstly civil protection agencies, and in the general public, when it comes to forecasts which affect human lives and critical infrastructure flood warnings are routinely issued to the public and used to inform civil protection authorities during events. Secondly, hydrological forecasts can be used for economical purposes, such as waterpower or water resources.

2.1.7. Pros and cons of the methodology

Hydrological forecasting is a well-established discipline from a scientific and technological point-of-view. Operational forecasting has a long history of development and is constantly improving. Automated systems for accessing data, running models and providing output guarantee a very high service level. Ensemble forecasting has been around for a very long time and is a good estimator for uncertainty, and there are many real cases which can be used to validate and further improve the methods.

Data availability and quality pose significant challenges that impact the accuracy of flood impact forecasts. To develop comprehensive flood models, it is imperative to have extensive datasets that encompass topographic, land use, hydrological, historical flood data, and water management practices. The efficacy of these models is directly influenced by the quality and completeness of the utilised data. However, it is frequently encountered that this data is outdated, inconsistent, or even missing, which will negatively affect the results.

It is difficult to accurately capture both high and low flow extremes, which can compromise the model's overall performance. Additionally, reliance on specific calibration metrics does not always guarantee reliable extreme event reproduction.

Flood models are uncertain due to the complexity of the underlying processes and limitations in the available data and models. To tackle these challenges, various methods exist in the literature to quantify uncertainty, including Bayesian inference, Monte Carlo simulation, and probabilistic sensitivity analysis.

2.1.8. How will GOBEYOND take this to the next level?

The most important aspects of flood impact forecasting in the future are both conceptual and technical. Climate change and human interaction on their environment will affect flood risk, and it is increasingly important to take this into account when forecasting flood risk. Accounting for how climate change and human activities affect complex hydrological processes could provide breakthroughs in flood forecasting accuracy and reliability (Di Baldassarre et al., 2019).

Recent development in the use of machine learning (ML) and use of artificial intelligence (AI) in flood modelling is very likely to become more common on the coming years thanks to the computational speed and accuracy (Karim et al., 2023). The flood impact application has in for example EFAS relied on a catalogue of pre-existing flood inundation events. With faster methods this may be become feasible to do on demand in future system, either as a hybrid solution or a pure ML-driven framework.

This can also entail better use of remote sensing data. Advanced ML algorithms can be employed to refine predictions dynamically, for example, physics-based ML for flood detection, monitoring and forecasting using remote sensing SAR data; use of both Sentinel-1 SAR images for flood detection and Sentinel-2 MSI pre-event images to learn the contextual information. **GOBEYOND** will employ novel techniques in calculating impacts of flood using an alternative deep-learning approach to predict river flood inundation spatial extent at <1 km spatial resolution. This approach has a much lower computational cost to generate forecasts, furthermore the training process will calibrate the model against remotely sensed observations. The approach will develop a U-Net model (Hosseiny, 2021), using inputs including EFAS river discharge and land cover and floodplain elevation from the Copernicus Land Monitoring Service. It will be trained against satellite observations of flood extent and be compared with current catalogue of pre-existing flood extent. The impact-based forecast will consider human interaction and future climate change.

2.2. Flash floods

2.2.1. State-of-the-art and objectives

Flash floods (FFs) are the result of extreme precipitation exceeding natural or man-made drainage system capacities (Seneviratne & Zhang, 2023). Typically, these affects small to medium size catchments (up to a few hundreds of square kilometres) characterised by steep topography and prone to convective storms. The timeframe of these events can range from the order of 10 minutes to a few hours, making them explosive in nature and with limited time for warning issuing or the activation of emergency response protocols. Therefore, monitoring and forecasting flash floods is a crucial challenge exacerbated by the influence of climate change.

Worldwide, there have been several initiatives to develop real-time FF forecasting systems. A noteworthy example is the Flash Flood Guidance (FFG), currently operated in the USA and Central America (Clark et al., 2014). The method consists in triggering an FF warning once the forecasted rainfall surpasses the critical threshold (determined by running a rainfall-runoff model) for overtopping the riverbanks. A parallel approach is to exclusively compare rainfall (observed and forecasted) to established intensity-duration critical thresholds in real-time. Due to its simplicity, low implementation costs and data needs, a number of operational FF-EWS prefer this rainfall-based for large and ungauged areas. The next sections provide the overview of the radar and rainfall-based FF-Early Warning System (FF-EWS) developed by the Center of Applied Research in Hydrometeorology at the Universitat Politècnica de Catalonia (CRAHI-UPC).

2.2.2. Principles and elements of theory

The FF-EWS utilizes quantitative precipitation estimates and forecasts (Quantitative Precipitation Estimation - QPE and Quantitative Precipitation Forecasting - QPF, respectively) to derive flash flood warnings over the drainage network. For this, the system works under the assumption that the FF hazard at a point D (in terms of the exceeded return period) in the drainage network can be characterised by the rainfall accumulated upstream over its specific concentration time (i.e., basin-aggregated rainfall). This hypothesis specially holds for high return period events where the response of the catchment is mainly controlled by the rainfall amount, and thus, leading to similar slopes for the discharge and rainfall cumulative probability distribution functions (Guillot & Duband D., 1967).

Specifically, on hazard assessment, the basin-aggregated rainfall is computed at each cell of the drainage network and in a timeframe equally to its concentration time with the Kirpich (1940) formula. Operationally, the system works in real-time with pre-defined durations, and thus it selects the duration closest to the concentration time of the pixel. An additional assumption is made if a reservoir is located within the drainage network. At this location, the basin is split, and the upstream basin is not included in the calculations (assuming total discharge regulation).

As explained before, the computed basin-aggregated rainfall is compared to a set of thresholds to determine hazard level in terms of exceeded return period. These thresholds should be related to the climatology of the basin-aggregated rainfall, such as the available Intensity-Duration-Frequency curves. At each computation step when QPEs (and QPFs) are available, the basin-aggregated rainfall is computed at the individual cells over the drainage network considering their concentration time. Then, a comparison is made between the basin-aggregated rainfall and the thresholds to determine the value of the exceeded return period for the upcoming event.

2.2.3. Operational platforms for alert visualization and dissemination

The UPC-CRAHI's FF-EWS is used at different spatial and lead time scales:

- Continental scale using European radar composites (OPERA) and nowcasts with 6 hours lead time. The spatial resolution scale is 1 km, and the nowcasts are refreshed every 15 min. The FF hazard level can be presented in terms of exceeded return period or in a three-level traffic-light scale (yellow: low, orange: medium, red: high) following the regional climatic characteristics as published by the MeteoAlarm consortium (Figure 5).

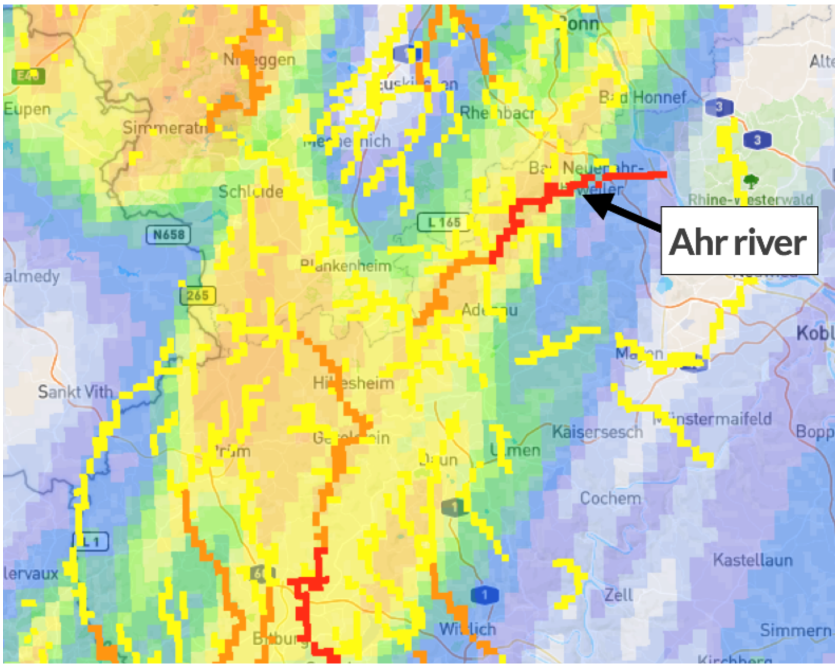


Figure 5 2021 European floods: Maximum FF hazard level forecasted by the FF-EWS in the Ahr river on the 14/07/2021 at 14 UTC for 19 UTC (5-hours before the observed impacts)

- Regional scale based upon regional radar observations and nowcasts with lead times of 2-6 hours. In Catalonia, the FF-EWS runs at a spatial scale of 200 meters, and the nowcasts are refreshed every 5-10 min.

2.2.4. Validation

The FF-EWS performance has been widely tested across different regions, scales and climatology. Overall, the evaluations yielded encouraging results on the ability of the FF-EWS to identify the problematic sections in the drainage network during intense rainfall events with enough lead time. The outcomes demonstrated that the system is capable of locating significant hazard levels in the main areas where the most damaging floods occurred, up to almost 2 hours ahead (Alfieri et al., 2019). Moreover, when compared to the traditional flow-based flood forecasts, the FF-EWS results indicate a good agreement in terms of the warnings triggered by both systems, the observed flow discharge and the reported inundations (Corral et al., 2019).

For more information on the latest evaluations, outcomes and applications of the FF-EWS at different scales see (Alfieri et al., 2019; Corral et al., 2019; Meléndez-Landaverde & Sempere-Torres, n.d.; Ritter et al., 2020).

2.2.5. Latest work: Probabilistic information and Impact assessment

Since 2018, a back-to-back of three EU Union Civil Protection Mechanism (UCPM) projects have provided the platform for innovative advancements to the FF-EWS. During the UCPM SMUFF project (2018-2019) a seamless and dynamic blending of probabilistic radar-based nowcast and numerical weather prediction model was developed to increase the precipitation forecasting window from 15 minutes to 5 days. As a result, the FF-EWS was ran and tested with the rainfall inputs from the above blend to provide FF hazard levels with extended lead times at Pan European scale.

In the second project TAMIR (2020-2022), the FF-EWS was improved by combining the FF hazard forecasts with enhanced vulnerability and exposure data, covering information about population, transportation infrastructure, energy infrastructure, education facilities and health facilities, and by developing methods to turn the combined information into improved flood rapid risk impact assessments. Finally, the latest project EDERA (2023-2024) inherits the results of the two above projects and focuses on the real-time application of the FF impact forecasts (through its incorporation in EFAS) to evaluate its performance at Pan-European and regional scale.

2.2.6. End users

The concept of the rainfall-based FF-EWS was first developed within the EHIMI project (2001-2010), and operationally applied in 2008 at the Water Agency of Catalonia (ACA) in Spain (Corral et al., 2009). The concept of rainfall-based FF-EW was further developed in the framework of the FP7 EC project IMPRINTS, setting the foundation for the European Precipitation Index based on Climatology (EPIC), integrated operationally in EFAS since 2012. EPIC index has since evolved to the indicator ERIC which considers the antecedent soil moisture.

The FF-EWS system was implemented at European scale in the context of the DG-ECHO project ERICHA. The system uses the radar composites produced by the EUMETNET programme OPERA to generate FF forecasts with a resolution of 1x1 km^2 in real-time. In the ERICHA indicator, the FF hazard level is presented in a three-level traffic-light scale following the regional climatic characteristics as published by the MeteoAlarm consortium. Since 2017, the FF- EWS runs operationally as the radar-based flash flood forecasting module for the EFAS, serving as a complement to the ERIC product.

During the H2020 ANYWHERE project (2016-2019), the FF-EWS was improved to run at a 200-meter resolution over the entire Catalonia region. This iteration is currently operational in real-time at the Catalonia Meteorological Service (SMC), ACA and within the ARGOS warning platform for municipalities, civil protection, private entities and regions across Spain and Europe (Corral et al., 2019).

2.2.7. Pros and cons of the methodology

The FF-EWS relies exclusively on precipitation information, providing advantages and limitations. In contrast to streamflow models, the calibration of parameters is not needed in the FF-EWS to assess the FF hazard level. Although this can facilitate the system's implementation over large and ungauged domains, this simplification overlooks initial conditions that can impact the catchment response (e.g., initial moisture state).

Since precipitation is the main input for the FF-EWS, the system's performance relies on the quality of the QPE maps. Radar QPE accuracy can be affected by beam blockage, bright-band effects, attenuation, and calibration inconsistencies between radars, especially in complex terrain (Bližňák et al, 2014, Borga et al., 2000; Park et al., 2019). For instance, in mountainous areas, errors often arise from beam elevation, the variability of precipitation with height, and contamination from ground returns (Borga et al., 2000). Corrective algorithms like mean-field bias adjustment, gauge blending, and vertical profile of reflectivity (VPR) correction can reduce, but not completely eliminate, these uncertainties. In the case of the FF-EWS, correction steps are implemented in real-time (Corral et al., 2009), although some depend on the availability of gauge data. To complement radar observations and help validation in data-sparse regions, operational satellite precipitation products (e.g, Climate Hazards Group Infrared Precipitation (CHIRP), Satellite Application Facility on Support to Nowcasting and Very Short Range Forecasting (NWCSAF), COSPARIN) can be utilized (Bližňák et al., 2014; Dinku et al., 2018; Guillaume et al., 2021) (see section 2.2.8). Finally, the heterogeneity and coverage of the radar network, like OPERA, can require additional efforts and resources for scan strategies, data processing algorithms, and other calibration methods (Park et al., 2019).

Click or tap here to enter text.Nevertheless, the lack of calibration parameters and the high-resolution of the local radar based QPE maps allow identifying the areas at risk with high-resolution at the expense of a shorter lead time (up to 2 hours) (Alfieri et al., 2019).

2.2.8. How will GOBEYOND take this to the next level?

Due to the explosive nature of FFs, disseminating impact-driven warnings with sufficient lead to trigger protection actions is a complex task. However, previous evaluations of the FF-EWS have demonstrated that the algorithms to activate actionable solutions through local self-protection protocols are available. Thus, the main challenge is how to use this technology to empower the population and emergency responders to take appropriate actions to protect themselves and their communities. In this context, the planned demonstrations in **GOBEYOND** will provide an excellent platform to understand how to best improve and integrate the FF hazard levels as one of the activation warning signals for quickly deploying emergency responders and to support the self-protection actions of citizens.

In addition, within the framework of the project, the FF-EWS model could be fed with alternative data sources in areas where radar observations are not available. This is the case for several Mediterranean countries, where satellite rainfall estimation data can address this limitation, providing a worldwide coverage. In this context, the COSPARIN dataset (Spatial contribution for flood risk analysis), developed through a European project with the European Space Agency (ESA) and led by PREDICT Services, constitutes an important asset. It combines geostationary data and polar satellite observations with an artificial intelligence model to produce global rainfall estimates every 30 minutes at a 5km resolution.

This dataset can be integrated into the FF-EWS model to support the identification of flood alerts across Mediterranean river basins. This is supported by the validations made in previous years. Since 2020, COSPARIN data has been systematically assessed through comparisons with more than 200 significant rainfall events worldwide. Successive iterations of the dataset have incorporated user feedback as well as validation results, leading to continuous improvements in accuracy and operational reliability. The most recent versions therefore reflect extensive input from civil protection authorities, national meteorological services, and other institutional users.

Figure 6 presents a significant rainfall event in northern Morocco and compares outputs from four datasets. The COSPARIN data allows to an accurate assessment of cumulative totals and to identify the corresponding watersheds.

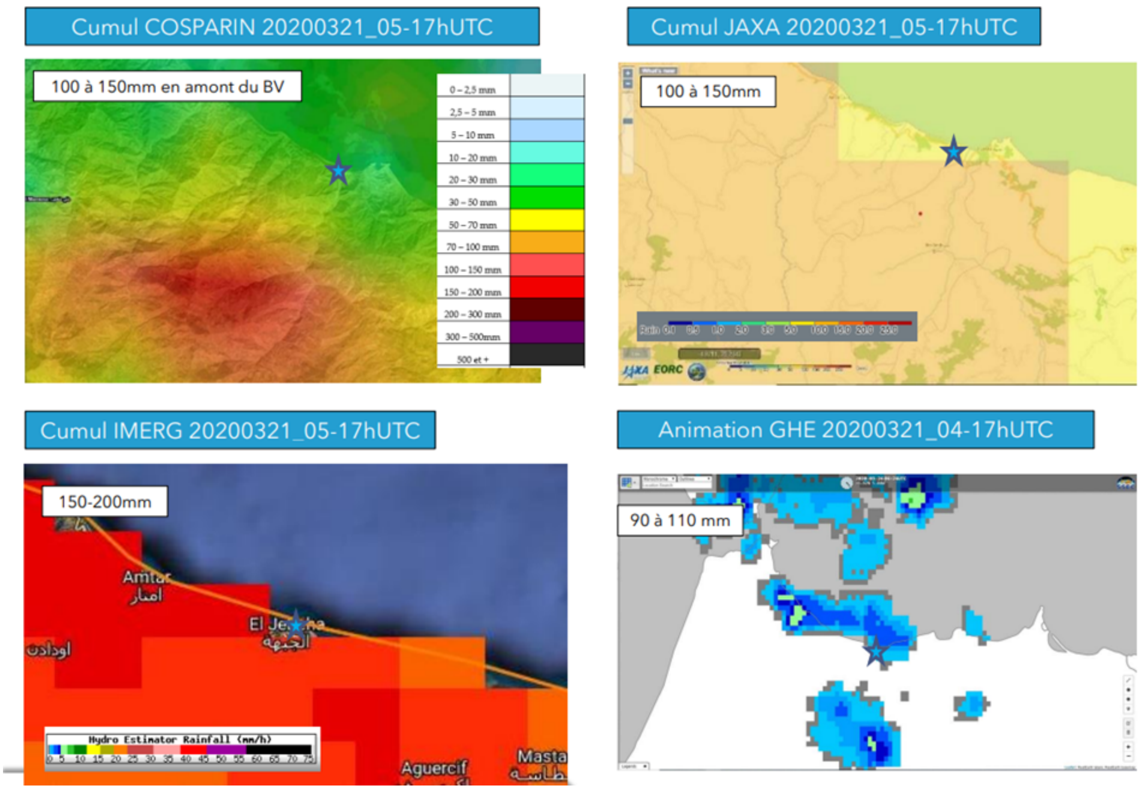


Figure 6 Comparison of rainfall estimations in northern Morocco for March 21, 2020

2.3. Windstorms

2.3.1. State-of-the-art and objectives

Storms are one of the most damaging weather-related hazards worldwide, and the intensity and damage depend on the nature of the system. Tropical cyclones, such as hurricanes and typhoons, form over warm waters and can be devastating when they make landfall. Europe is not directly affected by tropical cyclones, but the systems that form in the Atlantic are affecting the Western part of Europe in later stages. Winter storms and Medicanes are other features that affect Europe.

This chapter will focus on (winter) wind storm forecasting in Switzerland (Imhof, 2011) as an illustrative example of a storm forecasting system. The main documented impacts of storms in Switzerland are damage to buildings and infrastructure, interruption of rail and road traffic, electricity blackouts, forest damage, and loss of life during or after the event (Scherrer et al., 2018; WSL & BUWAL, 2001). In January 2018, for instance, winter storm Burglind (Eleanor) caused damage to Swiss infrastructure estimated at CHF 165 million (EUR 185 million), interruptions in traffic and the electricity grid, and to 1.3 million cubic meters of forest wood (Scherrer et al., 2018). Besides winter windstorms, thunderstorms, and foehn are the predominant storm phenomena inflicting impacts in Switzerland (Röösli et al., 2021).

Most national hydrological or meteorological services (NHMS) in Europe warn purely based on hazard information yet plan to incorporate impact information into their warning systems (Kaltenberger et al., 2020). However, practical challenges such as IT infrastructure to produce quantitative impact forecasts, lack of impact data, transdisciplinary collaborations, and legal or responsibility obstacles persist (Kaltenberger et al., 2020; Röösli et al., 2021). Storm impact forecasting systems are known in the private domain, e.g., through proprietary models run by insurance companies (Pinto et al., 2019). In the public domain, this is much less common; one operationally successful implementation was illustrated by the vehicle overturning model of the UK Met Office (Hemingway & Robbins, 2020).

In a proof-of-concept, a quasi-operational impact forecasting pipeline for winter storm damages to buildings has hence been developed at MeteoSwiss (Röösli et al., 2021). While operationally, MeteoSwiss issues threshold-based hazard warnings for wind, this first demonstrator combined NWP models with building exposure and calibrated vulnerability data to forecast physical impacts. As a pre-operationally running product, it serves to further evaluate future feasibility of an impact forecasting system, its potential beneficiaries, and development (IT) needs for incorporating socio-economic impact forecasting into warning decisions by meteorological services.

2.3.2. Principles and elements of theory

A first pilot developed an open-source impact forecasting system for predicting storm-induced building damage in Swiss Francs with a 2-day lead time on a 500-meter grid or aggregated to administrative regions. Details can be found in Röösli et al. (2021). It utilizes the operational NWP model COSMO-2E by MeteoSwiss. This NWP model generates 21 ensemble forecasts with a 2.2 km spatial resolution and 60 vertical layers, twice daily for up to 5 days into the future. The focus is on predicting maximum wind gust velocity, crucial for warning decisions, with a lead time of 2 days.

To compute damages on buildings, i.e., impacts inflicted by these wind gusts, the risk assessment platform CLIMADA (Aznar-Siguan & Bresch, 2019) is employed. CLIMADA is an event-based, open-source and open-access, probabilistic tool developed at ETH Zurich, which allows for spatially explicit impact and risk calculations according to the IPCC's definition as product of hazard, exposure, and vulnerability. The platform allows to combine weather forecast data (the hazard component, where each ensemble member considered an event) with exposure data (geolocated building values) and vulnerability data (a function relating hazard intensity to expected consequence on the exposure) to produce expected building damage estimates. Figure 7 contrasts classic threshold-based, categorised wind warnings at MeteoSwiss with expected building damages in CHF from the impact forecast.

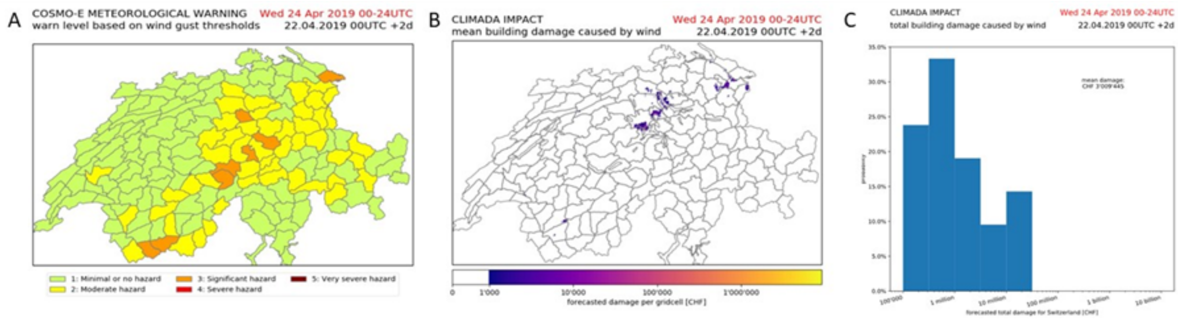


Figure 7 Wind warnings comparison

Panel A – hazard-based warning (classic) at MeteoSwiss: Warning levels (1-5) are determined based on physical thresholds of predicted wind gusts, refined by expert knowledge of forecasters, and spatially aggregated per warning region. Panel B – impact-based forecasts: Average wind-induced building damages in CHF are computed from combining the same wind gust prediction with building exposure and vulnerability data. Panel C – probabilistic distribution of total forecasted building damages

2.3.3. Technological requirements

The storm impact forecast utilizes the COSMO-2E model by MeteoSwiss for weather forecasts, LitPop, an open-source building value layer (OpenStreetMap contributors; Eberenz et al. 2021), and the risk assessment platform CLIMADA for impact modelling. The underlying model was calibrated based on proprietary building insurance data from the cantonal building insurance of Zurich (GVZ). The computation chain automatically runs every time a new forecast is issued (i.e., every 12 hours), and past result layers are stored internally. As a pre-operational demonstrator, no official warnings are derived from this impact layer.

2.3.4. Operational platforms for alert visualization and dissemination

As the winter storm impact forecast is not operational, no alerts are issued, visualized or disseminated. It runs on a MeteoSwiss-internal server which produces geographic maps of impact hotspots and quantitative statistics on aggregate impact distributions (Figure 7) on a non-public API.

2.3.5. Validation

Aggregate daily building damage records from GVZ were used to verify the forecasted building damages for a 3-year period. Additionally, higher-resolution building damage records for specific events like storm Burglind/Eleanor on 3 January 2018 were available for in-depth validation. Sensitivity analysis was conducted to understand uncertainties in hazard, exposure, and vulnerability and to assess their impact on forecasted total damages by systematically sampling from ensemble members (meteorological uncertainty), perturbing valuation factors and disaggregation methodologies (exposure uncertainty), and re-calibration of impact functions (vulnerability uncertainty).

2.3.6. End users

This proof-of-concept emerged as part of an academic dissertation and did not target the prime interest group of MeteoSwiss. As is, it would primarily be of use to large public or private entities such as insurance companies. MeteoSwiss, however, aims to develop impact-based warnings which benefit federal and cantonal authorities, civil protection agencies, and the public.

2.3.7. How will GOBEYOND take this to the next level?

Engaging with stakeholders in two "test cantons" throughout the **GOBEYOND** project will help to develop and improve actionable impact warnings by determining relevant impact metrics, by unlocking (impact) data and knowledge of future partners, and by fostering collaboration between meteorological services and practitioners for enhancing communication and decision-making during extreme weather events.

For instance, there will be no constraint on the hazard layers – MeteoSwiss produces ML-based forecasts ("Coalition4") which capture the behaviour of local thunderstorm cells with lightning, precipitation, and hail, which will be integrated to better track the multi-hazard impact of these convective phenomena. The overall platform and model (CLIMADA) is an enabler to provide a framework which can be tailored and filled with stakeholder-specific products. Collaboration with other **GOBEYOND** partners on more relevant hazards (for instance, flash floods and surface run-off) is also already ongoing.

Further, representing uncertainties at different geographical scales and managing false alarms and missed events (especially from thunderstorms, which are locally intense and harder to predict, but also foehn phenomena) remains challenging. Within **GOBEYOND**, a work-package focusing on uncertainty visualization and communication, both on the meteorological part and on the impact end-scale, is in progress. Aspects include focusing on specific realizations (best case, worst case, "expectable" case), providing aggregate statistics (such as mean, median, variance) over user-provided geographic areas, setting probability thresholds for alerting, and time series progressions of uncertainty.

Another key challenge is to move away from impact metrics focusing on monetary losses, since these present little short-term mitigation options in the civil protection domain. The longer-term goal is to develop *actionable* impact forecasts, which enable civil protection agencies and authorities to take concrete steps to reduce impacts of all relevant weather phenomena. Here, transferability of the presented storm damage chain to other impact types and hazards is hampered due to frequent lack of calibration and validation data. A significant part of the efforts in the **GOBEYOND** activity of the Swiss pilots those goes into collecting case-specific exposure and impact data from our stakeholders which are emergency-response relevant; they include number of calls to emergency dispatch centres, and vulnerable sites.

While the Swiss pilots naturally focus on national case studies and weather forecast / climate data supplied by MeteoSwiss for the area of Switzerland, the method development with CLIMADA and a stringent risk framework has a major advantage: Transferability to other regions is straightforward. In **GOBEYOND**, demonstrators have already been developed that employ the risk modelling chain and CLIMADA for a pan-European case study using ECMWF IFS forecast data for people exposure and asset damage from precipitation and wind.

Lastly, challenges such as IT infrastructure, data collection, legal and political obstacles, and partner collaboration need to be addressed for successful implementation. While MeteoSwiss intends to operationalise, national prototypes using its own IT infrastructure, the pan-European CLIMADA demonstrators are evaluated to be hosted on ECMWF's European Weather Cloud, through **GOBEYOND** resources.

2.4. Storm surges

Storm surges are complex oceanographic phenomena that can have significant impacts on coastal communities, particularly during extreme weather events such as hurricanes, typhoons, and extratropical cyclones. In practice, a storm surge is a major coastal flooding driver (Resio & Westerink, 2008). Storm surges constitute a temporary increase in sea level that persists for several hours and can not only cause coastal inundation but also increase the wave-driven hazard, i.e., erosion (Shaw et al., 2016) and coastal protection failure (Hatzikyriakou & Lin, 2017).

Historically, devastating storm surges have caused catastrophic loss of life and large economic damage. Notable historical surges include those from the Bhola cyclone, Cyclone Nargis, Typhoon Haiyan Galveston hurricane and Cyclone Mahina. Recent examples include the unprecedented storm surges from Hurricane Katrina and Hurricane Sandy, highlighting the ongoing threat posed by these phenomena (Soomere & Pindsoo, 2016). On top of that, global warming is expected to increase extreme sea levels and coastal flooding around the world (Vousdoukas et al., 2018).

2.4.1. State-of-the-art and objectives

The storm surge phenomenon results in an abnormal rise in water level, leading to coastal flooding and potential erosion due to wind waves. Storm surges are driven by wind-induced water circulation towards or away from the coast, as well as atmospheric pressure changes, known as the inverse barometric effect (WMO, 2011). The magnitude of a storm surge depends on various factors, including the size, track, speed, and intensity of the storm system, as well as nearshore bathymetry and coastline shape (Arns et al., 2015). Given that weather patterns vary at time scales ranging from hours to decades, having high-quality time series which span several decades is essential for most studies concerning the dynamics of extreme sea levels (Haigh, et al. 2016). In addition, it is very important for policy making and the design of adaptation policies especially in view of climate change.

Understanding trends in past and future coastal hazards requires accurate modelling of waves and storm surge at a global scale, integrating the mutual impact of wind-waves and storm surge within a coupled framework. Recent advances in numerical modelling, computing power, and coastal observations have facilitated the development of global models providing valuable insights for coastal hazard assessment and risk management (Vousdoukas et al., 2018). While existing large-scale coastal hindcasts and reanalyses generally perform well compared to satellite observations offshore, limitations arise closer to shores due to complex coastal features and interactions, low resolution, and the lack of coupling between waves and circulation. Additionally, the dynamic interaction of coastal circulation, wind waves, inland hydrology, ice, and atmospheric models is not fully captured in standalone or one-way coupled fashion (Abdolali et al., 2020).

Apart from modelling the storm surge phenomenon at a global, it is also crucial to do it locally or regionally. For accurate hazard quantification, downscaling to regional and local levels is essential to incorporate high-quality environmental and socio-economic data. Information at these scales enables the forecasting of real impacts and risks associated with storm surge hazards, facilitating quasi-real-time coordination of emergency response operations during and after extreme storm surge events (Fernández-Montblanc et al., 2020).

2.4.2. Principles and elements of theory

Modelling storm surges involves fluid dynamics, meteorology, coastal engineering techniques, complex hydrodynamic and atmospheric processes. The key elements involve:

- Defining the domain: Determine the geographical area over which the storm surge will be modelled. This includes identifying coastal regions, bodies of water, etc.
- First principles modelling: Develop mathematical equations that describe the fundamental physical processes governing storm surges. These equations typically include the conservation of mass, momentum, and energy, such as the shallow water equations or Navier-Stokes equations.
- Boundary conditions: Specify boundary conditions that describe the behaviour of the water at the boundaries of the modelling domain. This includes factors such as tide levels, wind patterns, atmospheric pressure, and coastal topography.
- Numerical methods: Select appropriate numerical methods for solving the equations, e.g. finite difference methods, finite volume methods, or finite element methods.

Note that the shallow water equations are particularly useful for modelling large-scale phenomena such as oceanic tides, storm surges, and tsunamis, where the water depth variations are relatively small compared to the horizontal length scales. They provide a way to studying these phenomena over large spatial domains and long time periods.

Some well-established storm surge models used include the SELFE model, the SLOSH model (the Sea, Lake, and Overland Surges from Hurricanes), the ADCIRC model (ADvanced CIRCulation coastal circulation and storm surge model,) and CH3D-SMSS (the Storm Surge Modelling System with Curvilinear-grid Hydrodynamics in 3D). Other storm surge models include Delft3D and the Japan Meteorological Agency's storm surge model. See Appendix A.1 for a full description of the models.

2.4.3. Technological requirements

Depending on the type of storm surge model and the early warning system/forecasting objective, the technological requirements can vary. However, some baseline requirements are as follows.

- Sensor networks:
    - Tide gauges: Deploying tide gauges along coastlines to continuously measure water levels is critical since tide gauges provide (near-real-time) data for monitoring storm surge development.
    - Weather stations: It is necessary to have weather stations equipped with instruments to measure meteorological parameters such as wind speed, atmospheric pressure, temperature, and humidity.
    - Buoys: Deploying buoys equipped with sensors to measure wave height, direction, and period, provide valuable information about wave conditions in coastal waters.
    - Radar systems: Utilizing coastal radar systems to monitor precipitation patterns, track storm movements, and detect potential storm surge events. High-frequency radar systems can provide crucial (near-) real-time data.
- Spatial and temporal scale of operation:
    - Robust and modular numerical models: There is need for numerical models that can simulate storm surge dynamics at fine spatial resolutions to provide detailed forecasts for specific coastal regions.
    - Real-time data assimilation: Integrating real-time observational data from sensor networks into numerical models can improve forecast accuracy and reduce uncertainties.
- Automatic and manual data processing and analysis:
    - Data processing: There are algorithms, tools, toolkits that can automatically process and analyse large volumes of observational data. Depending on the tidal gauge technology there might be need for manual processing.
    - Expert interpretation: Meteorologists, oceanographers, and hydrologists might need to manually interpret model outputs, validate forecasts, and provide expert guidance to emergency managers and decision-makers.

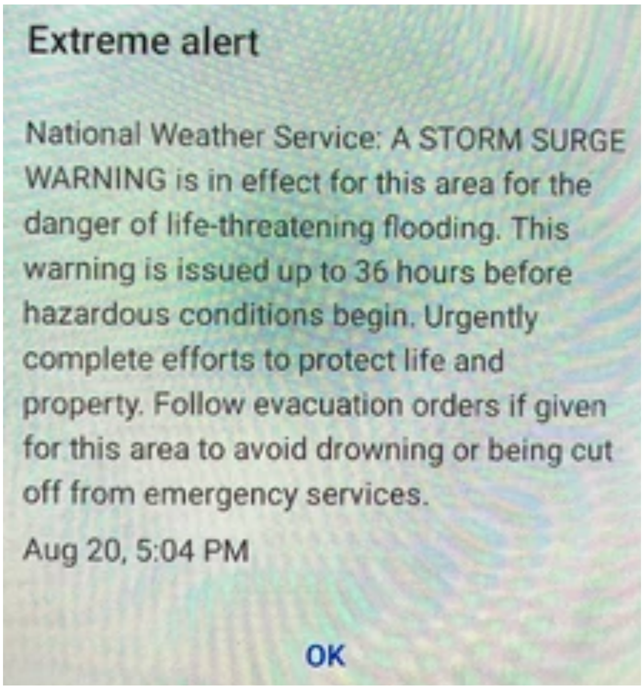


Figure 8 Example of a storm surge warning sent to a mobile app.

- Data transmission and alert communication:
  - Early Warning Systems: Able to rapidly disseminate alerts and warnings to via communication channels, e.g. mobile apps, text messages, email, social media, and sirens. An example of a storm surge warning is shown in Figure 8.
  - Public Alerting Platforms: Utilize dedicated platforms or systems, such as the Common Alerting Protocol (CAP), to ensure interoperability and compatibility with existing emergency communication systems.

Additional requirements involve integration with Decision Support Systems, e.g. Geographic Information Systems or forecasting tools. Finally, backup power systems are often required as well as alternative communication channels.

2.4.4. Operational platforms for alert visualization and dissemination

In addition to the state-of-the-art models and tools, there are operating platforms that assist with the study, forecasting or analysis of storm surges.

2.4.4.1. NOAA Tide Predictions

The National Oceanic and Atmospheric Administration (NOAA) provides tide predictions through its Tides and Currents website. Users can access tide predictions for various locations along the U.S. coastline, which can help monitor normal tide levels and detect deviations indicative of storm surges.

2.4.4.2. European Storm Surge Forecasting System in C3S

The Copernicus Climate Change Service provides climate data on storminess in European coastal seas, aiding in understanding the impacts of climate change and supporting long-term decision-making for coastal sectors. This includes flood management, flood control barriers, offshore wind farms, port operations, and coastal zone management. The service offers high-quality datasets of storm surge, tide, and wave conditions, incorporating sea level rise effects, both historically and in climate projections. Climate Impact Indicators (CIIs) derived from these datasets allow for comparing climate projections with historical baselines to assess the relative impact of climate change. Additionally, the dataset's usability is demonstrated through various use cases focusing on different coastal sectors and issues across Europe. These use cases highlight the application of sector-specific CIIs, such as evaluating climate impacts on British ports to devise effective strategies for mitigating climate risks. The use cases cover diverse coastlines and ocean regions in Europe, including the North Sea, Irish Sea, Atlantic Ocean, Baltic Sea, and Mediterranean.

2.4.4.3. A4EU/A4Cat Platforms

As indicated in (ANYWHERE, 2019), there are warning systems presented, developed, and extended within the context of ANYWHERE project. Storm surge technology was usable in EU and Spain in particular. Most modern systems operate in near-real time.

The relevant A4EU technical solutions and products involve:

- SMP Sea Status Warnings; official warning from local meteorological service in Spain
- Sea Status Warnings; official warnings from national meteorological service in Spain

- "Rissaga" Warnings; official warnings from national meteorological service in Spain
- "Galerna" Warning; official warnings from national meteorological service in Spain
- Sea surface level -- global; an Emergency Warning System for the whole Europe
- Sea surface level -- regional; an Emergency Warning System for the whole Europe
- Regional Storm Surges level; an Emergency Warning System for the whole Europe

2.4.5. Validation

The fundamental principle to validate storm surge models is to compare the computed storm surge against water level time series available from a reliable database of tidal gauges. The complete validation process for storm surge models is described in (Fernández-Montblanc et al., 2020). Model validation typically involves the following elements:

- Data Source: Water level time series data is obtained from the European Commission's Joint Research Centre (JRC) database of tidal gauges, which covers the entire computational domain with more than 200 tide gauges. The temporal resolution of the sea level measurements ranges from minutes to 1 hour, and the temporal coverage varies from one year to 35 years.
- Atmospheric Forcing Data: The Era-Interim atmospheric forcing dataset, developed by the ECMWF, is used for a long-period, multiannual verification spanning from 1979 to 2016. This dataset includes mean sea level pressure and wind velocity data.
- Comparative Analysis: A comparative analysis of the model performance using the forecasted and atmospheric datasets should be conducted.
- Evaluation Metrics: The performance of the storm surge model needs to be evaluated against some metrics. Typical key metrics involve:
    - Root Mean Square Error (RMSE)
    - Relative Root Mean Squared Error (%RMSE)
    - Pearson correlation coefficient (r)
- Spatial Variation Analysis: The spatial variation of the accuracy of the storm surge model predictions is visualized using error parameters across the computational domain.

2.4.6. Pros and cons of the methodology

A hindcast dataset (ANYEU-SSL) covering 40 years of Storm Surge Levels (SSL) data along the European coastline was developed within the ANYWHERE project and showed an average RMSE of 0.10 m compared to tidal gauge data and 0.07 m compared to satellite altimetry data. The hindcast, while valuable, has limitations, particularly in its tendency to underestimate extreme storm surge levels. This has implications for hazard and risk assessments, especially in areas where the bias exceeds 0.2 meters. Using the dataset directly could result in hazard underestimation, but statistical correction using available time series of non-tidal residuals (NTR) can mitigate this issue. Higher resolution models could help. Regarding the European Storm Surge Model, several factors may contribute to reducing the robustness of storm surge level and wave forecasting under future sea level scenarios. Sea level rise, changes in tidal patterns, and alterations in precipitation and river discharge could impact the model's performance under future climate scenarios. The Regional Storm Surge model's reliability is closely tied to projected sea level rise and rising river flood risks, necessitating potential remodelling or re-evaluation if significant changes occur in these parameters.

2.5. Heat waves

2.5.1. State-of-the-art and objectives

Prolonged events of extremely hot weather, such as those affecting Europe in 2003 and the Pacific Northwest of North America in 2021, revealed the nature of heatwaves as a major threat to human health and ecosystems. Heatwaves are borderless hazards that may cause extra power consumption, worsen community health, impact water consumption and quality, and drive additional costs within the natural and built environments. Current systems are typically based on the prediction of air temperature and its anomaly during the warm period of the year, based on local climatological conditions. Atmospheric, ocean and land conditions influence the onset and spatio-temporal extent of persistent, abnormally high temperatures. The simulation and interplay of multiple Earth-system components by NWPs is therefore a necessary requirement for heatwave forecasting.

Topography also plays a role as dense, central areas of cities are hotter than the suburban and rural areas surrounding them. Lack of vegetation, urban canyons and the use of low albedo materials are some of the factors influencing the temperature, moisture, ventilation and insulation in urban areas, with the compounded effect of amplifying local temperatures as well as worsening the heat felt by humans. Although the urban heat island (UHI) is a well-known effect intensifying the detrimental impact of heatwaves on the local population and ecosystem, the predictive tools used today are not able to resolve urban areas and their distribution within due to the coarse resolution. Yet, the translation from heatwave hazard into heatwave risk requires high-resolution vulnerability factors to be considered for the population and the infrastructure exposed.

With a projected increase in frequency, duration and intensity, heatwaves demand for effective management and responsiveness plans based on forecasts able to provide reliable and timely information at timescales ranging from days to seasons as well as from continental to city-level scale.

2.5.2. Principles and elements of theory

Heatwave forecasting consists in predicting three key features: the magnitude of the heatwave, i.e. the departure from normal, reflecting the climatological extremity of the event; its duration, i.e. the length of time elevated temperatures lasts; its extent, i.e. the geographical area where the heatwave occurs. Magnitude, duration and extent are in general defined with respect to air temperature, with the latter depicted by means of daily maximum, minimum or daily average values.

Global NWPs are used to produce deterministic forecasts of heatwaves with individual hot days predicted out to about 10 – 14 days into the future. Beyond this time horizon, forecasts are expressed probabilistically from an ensemble of scenarios to consider for the model’s uncertainty. Sub-seasonal forecasts (i.e., 3-week lead time and beyond) are usually in the form of weekly averages and departures from a long-term climatology and are aimed at the identification of large-scale patterns leading to heatwaves.

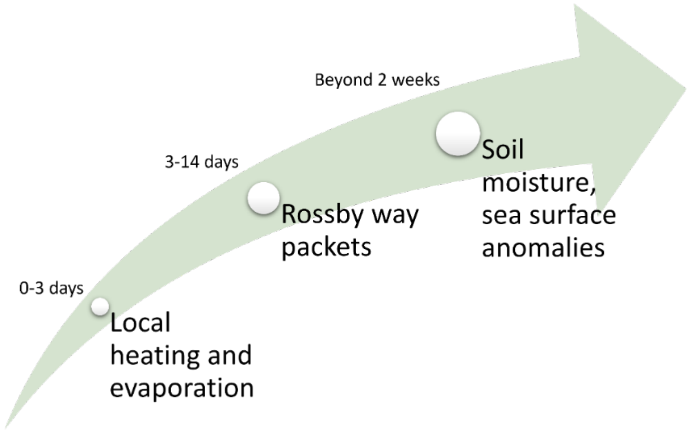


Figure 9 Key factors influencing heatwave forecasting at different timescales.
Source: Adapted from Magnusson et al. (2023).

Extratropical atmospheric blockings, i.e., strong and slow-moving high-pressure systems that remain in place over an area for a period of time, are the canonical drivers of heatwaves. Other drivers include soil moisture and ocean surface anomalies, as well as feedback processes such as the land–atmosphere coupling. These phenomena, whether local or remote, influence the skilfulness of heatwave forecasts across timescales (Figure 9).

2.5.3. Technological requirements

To be meaningful across multiple spatial and temporal scales, heatwave forecasting must meet three interlinked technological requirements: modelling, historical data and location-specific information.

Physical models and statistical models are the two prevailing tools for heatwaves forecasting. Physical models solve prognostic equations to quantify energy and matter exchanges between the ocean, atmosphere, and land, thus simulating potential heatwave drivers. Their spatial resolution ranges from ~100 km in global climate models to a few kilometres in mesoscale weather models. Statistical models are based on measurements or reanalysis datasets downscaled to urban scales. Their data-driven approach is used to detect potential correlations between temperature and other meteorological variables.

Location-specific observations have a two-fold purpose in heatwave forecasting. First, via data assimilation, observations from *in situ* weather stations are combined with short-range forecasts to obtain the best possible estimate of the current state of the Earth system. That estimate, called the analysis, is used as the initial conditions on which weather forecasts are based. Its accuracy is crucial to the quality of forecasts and hence to the decision-making process associated. Erroneously mild forecasts, for instance, have been shown to increase human mortality (Shrader et al., 2023). Secondly, sensor networks (fixed or mobile) can be used as sources of temperature measurements at fine resolution. Combined with prediction models via downscaling or AI techniques, they allow spatiotemporal temperature variations in topographically challenging areas, such as in cities, to be resolved.

Whether from measurements or reanalysis databases, long timeseries of historical temperature data are necessary to define the climate normal, i.e., the reference threshold (e.g., the 95th climatological percentile) against which temperatures can be characterised as a heatwave or a non-heatwave event. Data should be quality-controlled and embedded in computational environments that allow reliable storage of large datasets as well as their efficient retrieval and use for the calculation of the climate normal. The environment should also fit for the automatic detection of a heatwave event from forecasts as soon as the latter are issued.

2.5.4. Operational platforms for alert visualization and dissemination

To date, no global product exist that provides forecasts of heatwaves by considering their magnitude, duration and extent at once. There are however forecast products that target some of the heatwave features and may aid towards the management of the hazard. One of such products is the extreme forecast index (EFI), by the European Centre for Medium-Range Weather Forecast (ECMWF). The EFI is an integral measure of the difference between the ensemble forecast distribution and the model climate distribution. The EFI takes values from –1 to +1, with magnitudes of 0.5-0.8 (resp. above 0.8) irrespective of sign signifying “unusual” and “very unusual” weather. Although larger EFI values indicate that an extreme event is more likely, the values do not represent probabilities as such. Institutions such as the Australian Bureau of Meteorology (BoM) have implemented regional heatwave forecasting systems based on their operational forecasts.

As for monitoring, the European drought observatory (EDO) provides a platform for detecting and characterizing past-to-near present periods of extreme-temperature anomalies. In EDO heatwaves are calculated from a gridded observational product as three or more consecutive days with both daily minimum and maximum temperatures above the 90th climatological percentile daily threshold (Lavaysse et al., 2018).

2.5.4.1. Heat waves on the local scale: example from Switzerland

Heat is considered a serious natural hazard for human health, infrastructure, and ecosystems (Burgstall et al., 2021). In Switzerland, heat stress has strongly increased in recent decades; IPCC and CH2018 climate scenarios predict even more frequent and intense heat waves in the future (MeteoSwiss, 2024). As a response, MeteoSwiss has recently refined its heat warning system to incorporate new scientific insights, to develop a coordinated approach with other governmental bodies, and to analyse and communicate both heat warnings and climatology-related heat initiatives.

Heat indices and warnings have traditionally incorporated a combination of temperature and humidity - such as wet bulb temperatures, or - as a measure of *perceived temperature (PT),* whose (site and pre-condition specific) maximum daily value is linked to a duration-of-exceedance threshold (typically 3 days) to trigger warnings; see the state-of-the-art review in (Casanueva et al., 2019) on 15 national heat warning systems for details. However, as scientific insights are advancing, numerous epidemiological studies in Switzerland (Ragettli et al., 2017) and across the globe (Armstrong et al., 2019) have repeatedly shown that heat-related health risks, such as mortality and morbidity, correlate rather with sustained high temperatures (including at nighttime) and short, intense heat periods. In collaboration with the Swiss Tropical and Public Health Institute (Swiss TPH), MeteoSwiss hence adopted the daily mean temperature as the new indicator for heat warnings, based thresholds on population-wide, epidemiological impact data (Ragettli et al., 2023), and introduced a new warning level to also address short and intense heat events. Moreover, it has become increasingly clear that the integration of pure heat warnings into broader heat-*health* warning systems is of utmost importance; several Swiss cantons and neighbouring countries (e.g., Austria and Germany) have since implemented coordinated response schemes (MeteoSwiss, 2024).

Despite focusing on imminent heat warnings in the Swiss context via the operational MeteoSwiss Heat Warning tool, initiatives on the broader implications of heat stress on society, including impacts on workforce health and productivity, and on long-term climatological implications are to be pointed out: The European Horizon 2020 HEAT-SHIELD project focused on developing larger-scale and longer-term heat warning systems and climate projections to protect workers and mitigate productivity losses (Casanueva et al., 2020), various studies have examined urban heat island effect in detail for Swiss cities (Gehrig et al., 2018) and investigated on individual as well as systemic adaption measures, including effective warning strategies (MeteoSwiss, 2024).

2.5.4.2. Heat warnings at MeteoSwiss

Heat warnings at MeteoSwiss have recently undergone a renewal. Previously, a two-level warning was issued for low-lying regions (<600 m.a.s.l.) in Switzerland if the Heat Index, a metric based on a combination of temperature and relative humidity or dewpoint, surpassed a fixed threshold during a critical duration of 3-4 days. This concept was oriented along the paradigm of perceived temperature and adopted from the approach initially developed at NOAA (Steadman, 1979, 1984).

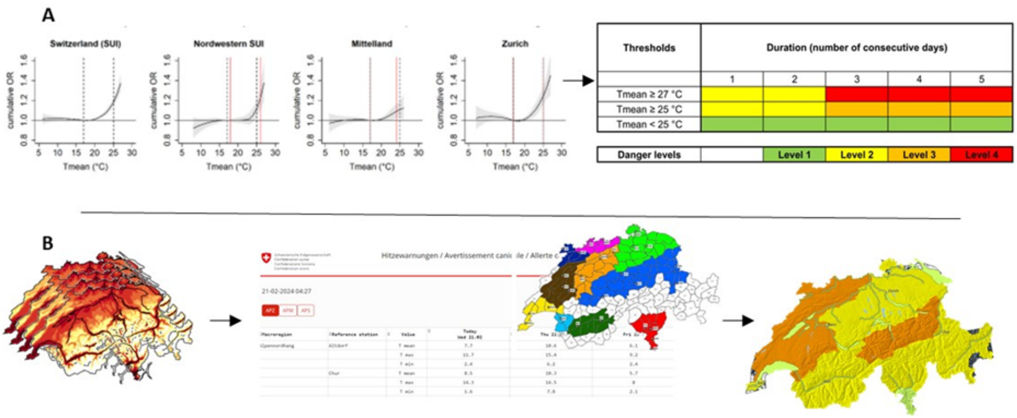


Figure 10 Meteo Swiss Heat-Warning Thresholds and Operational Warning Chain

A: Taking an exhaustive epidemiological evaluation of Swiss heat-mortality correlations as scientifically grounded decision basis, thresholds for heat warnings (levels 2-4) based on daily mean temperature projections (Tmean) were determined. Warnings of a duration >2 days (levels 3 &4) are communicated as “heat waves”, level 2 warnings are referred to as short “heat spells”. B: Operational warning chain: NWP data is processed and Tmean values derived, from which an automatic warning suggestion is generated for certain waring regions. Forecasters can hence amend these and issue alerts.

The novel heat warning paradigm, conversely, is centred around the key metric of *Tmean* over 24 hours. Drawing from an exhaustive epidemiological study utilizing mortality data from the Swiss National Cohort spanning from 2003 to 2016, daily mortality statistics alongside precise geographical coordinates and a comprehensive model incorporating both indoor and outdoor temperatures over the preceding 10 days have been analysed (Ragettli et al., 2023). The findings revealed critical thresholds for action, with temperatures exceeding 30°C marking a notable, and beyond 32°C a significant increase in mortality rates, even below expositions of 3 days, which used to be the previous duration threshold. Consequently, MeteoSwiss now issues heat warnings in 3 severity levels and already for shorter time durations, aligning with the new paradigm's insights. Notably, while the impact of humidity on well-being has been observed, it does not directly influence mortality rates; its indirect influence is accounted for within *Tmean* calculations, reflecting the diminished cooling effect at night during periods of high humidity (Burgstall et al., 2021). Focusing on *Tmean* further holds the advantage of amalgamating climate and weather metrics, leveraging over a century of measurements in Switzerland. An operational warning production chain now translates probabilistic numeric weather predictions into heat warnings levels derived from the hence-introduced thresholds. In addition to numeric levels, sentences declaring possible impacts and recommendations for actions are added to certain release channels.

Customized heat forecasts are currently provided to the health authorities of the French-speaking cantons of Switzerland, the canton of Ticino, and the canton of Valais. They are produced daily during the summer period by the respective regional forecast centres and are tailored to the needs of the health authorities, as developed in recent years in direct dialog. These services are particularly valued for preventive information for critical infrastructures (retirement homes, hospitals, etc.) and in "borderline" situations in which the heat threshold is not or barely reached across larger areas, but where heat stress can still occur in isolated cases.

Deterministic temperature data *Tmean*, *Tmin,* and *Tmax* are extracted at 5:30 am daily from MOSMIX, provided by the German meteorological office (DWD), for a set of "representative" reference stations (Figure 10, panel B). The MeteoSwiss heat warning tool classifies this NWP data into warning levels according to threshold and duration rules described above. Automatic warning level suggestions for geographic macro regions of Switzerland are generated by averaging over several contained reference stations; forecasters on duty can then adjust warning levels for smaller warning regions within these macro regions manually and add a selection of sentences regarding possible impacts and recommended actions going out to the public warning channels.

The heat warning production chain runs operationally at MeteoSwiss; from NWPs key metrics such as *Tmin*, *Tmax,* and *Tmean* are derived and disseminated automatically on MeteoSwiss-internal operating platforms together with other internally used heat-related products such as wet bulb temperature, effective temperature and heat index. Automatic warning level suggestions can be adjusted manually by forecasters before release.

General heat warnings of level 3 and 4 are distributed in the same way as all other severe weather warnings; the main recipients are the authorities and the population. The authorities, both at federal and cantonal level, are informed via the secure VULPUS communication system via the cantonal police operations centre. The public is informed via the websites (MeteoSwiss and Naturgefahren) and via the MeteoSwiss app. Push alerts can be subscribed to free of charge on the MeteoSwiss app. Heat warnings are also sent to various federal offices, e.g., the Federal Office of Public Health, the Federal Roads Office or the Federal Office for the Environment, to the media (TV and radio stations) and to private weather services. Level 2 warnings are not classified as severe weather warnings and are therefore not distributed to the cantons through the official, secure channels. Bespoke heat-health warnings are distributed directly to the regional health authorities via the regional forecast centres, where personal exchange and advice may be added.

2.5.5. Validation

Weather forecasts provide skilful information on upcoming heatwaves up to 10–15 days ahead (Domeisen et al., 2023). The skill of heatwave forecasts is evaluated as the ability to predict dichotomous events, namely heatwave events against no heatwave events. Both probabilistic and deterministic skill scores exist and include the area under the relative operating characteristic curve (ROC), reliability, and the equitable threat score (ETS). The latter, for instance, assesses the consistency among ensemble members.

Predictive skills extend beyond the medium-range forecast horizon, with warm anomaly in the model ensemble observed up to lead-week 3 in Australia (Marshall et al., 2014), Europe (Wulff & Domeisen, 2019), India (Mandal et al., 2019), Russia (Vitart & Robertson, 2018), South America (Osman & Alvarez, 2018) and North America (Emerton et al., 2022; Tian et al., 2017). In general, the magnitude of a heatwave is found to be more predictable than its onset and duration.

At MeteoSwiss, a cross-comparison (rather than validation) has been performed because of the recent change of metric on which the issuing of heat alerts is based at, evaluating the frequency, location and severity of warnings generated by various potential variables, on historic weather data spanning 1981-2017.

2.5.6. End users

Heat warnings are received by the general Swiss public, as well as national, cantonal and local authorities, federal offices, the media and private weather services through official distribution channels. Bespoke heat-health warning products are further generated against remuneration for a selected number of cantonal health offices.

2.5.7. How will GOBEYOND take this to the next level?

In recent decades, heatwave forecasting has gained attention and space in the decisional process of disaster management agencies. Although generally recognised as prolonged periods where temperatures are excessively hotter than normal, a unique definition for what “prolonged” or “excessively hotter” or “normal” mean does not exist. Rather, the definition of a heatwave is sector specific, depending on the type of community – climate or impacts related – and on its purpose for targeting this type of hazards. The health sector, for instance, would define a heatwave as the period of sustained how weather when an excess in mortality counts or admissions to hospital occurs. Furthermore, the definition of a heatwave would be domain specific too, as factors such as acclimatisation or vulnerability influence the heat-related impacts on exposed population, infrastructure and ecosystem. Metrics such as the excess heat factor (EHF) have been proposed as a global heatwave health impact indicator (Nairn et al., 2018), but its forecasting performance is yet to be proved beyond the regional scale.

On the local scale, MeteoSwiss has adopted an epidemiological, scientifically-informed approach to improve heat warnings, which better incorporates local conditions and impact-informed insights. However, heat sensitivity is also highly individual and influenced by a variety of meteorological and other factors such as medical preconditions, clothing, degree of acclimatization or type of occupation (Coccolo et al., 2016). Further, potentially relevant impact data to calibrate impact-based warnings, such as emergency hospital admissions, data from general practitioners, etc., is rarely accessible. Investigating the combination of several heat stress indicators, and the collection of actual impact data, might enable a more user or use-case specific, impact-oriented warning or information system.

2.6. Droughts

Droughts are a temporary decrease of the average water availability due for example to insufficient rainfall and are considered natural phenomena. Droughts can occur anywhere in Europe, in both high and low rainfall areas, and in any season. The impact of droughts can be exacerbated when they occur in a region with low water resources or where water resources are not being properly managed. This results in imbalances between water demands and the supply capacity of the natural system. Drought is to be distinguished from aridity, a long-term climatic feature, and from water scarcity.

Drought is one of the most damaging natural hazards in terms of affected people and economic cost. Between 1900 and 2010, worldwide two billion people were affected and more than 10 million people passed away, because of the impacts of drought. Such damages and losses are expected to become greater due to the projected increase of drought in multiple regions across the world under global warming. The need for drought impact forecasting has been internationally acknowledged in the framework of Multi-Hazard Impact based Early Warning System envisioned by the World Meteorological Organization.

2.6.1. State-of-the-art and objectives

Drought may refer to a wide collection of facts, usually closely related but still worth to distinguish. A classification according to the focus of the analysis may be useful:

- **Meteorological Drought** is based on the degree of dryness or rainfall deficit and the length of the dry period.
- **Hydrological Drought** is based on the impact of rainfall deficits on the water supply such as stream flow, reservoir and lake levels, and ground water table decline.
- **Agricultural Drought** refers to the impacts on agriculture by factors such as rainfall deficits, soil water deficits, reduced ground water, or reservoir levels needed for irrigation.
- **Socioeconomic Drought** considers the impact of drought conditions (meteorological, agricultural, or hydrological drought) on supply and demand of some economic goods such as fruits, vegetables, grains and meat. Socioeconomic drought occurs when the demand for an economic good exceeds supply as a result of a weather-related deficit in water supply.

When facing the forecast of drought impacts, there are several challenges. Here we outline some of them:

- Limitations on impact data make it difficult to directly relate hazard severity to the magnitude of impacts. Further, the relationship between hazard and impact is mediated by vulnerability, and there is a limited understanding of the dynamic factors that make individuals or communities vulnerable.
- It is often difficult to distinguish the impacts of drought form those resulting due to other causes. For example, food insecurity is a common impact targeted by drought programs, but food insecurity is a multi-hazard impact: it may arise because of a

number of independent hazards (e.g., hailstorms, pests, flooding), due to the combined effects of concurrent hazards, or because of non-biophysical factors (e.g., conflict, high food prices). It can therefore be difficult to determine if people are hungry for the “right” reasons (i.e., due to drought).

- There can be a mismatch between the predicted element of the hazard (e.g., seasonal rainfall total) and elements that drive impact (e.g., false onsets, dry spells, sub-seasonal rainfall distribution). Inferring the expected impact of a forecast is therefore difficult: on one hand, “below-normal” seasonal rainfall may still produce a reasonable harvest if rain is well-distributed throughout the season, but “near-normal” rainfall could cause harvest failure if rain occurs on extreme rainfall days, leading to inundation and crop destruction.

2.6.2. Principles and elements of theory

There are a number of available indices to choose from, and we refer to the WMO Handbook of Drought Indicators and indices (2016). The most used measure of drought is to compare a weather variable that impacts drought, e.g., precipitation, against its own climatology to calculate a standardised index, such as standardised precipitation index (SPI, Mckee et al., 1993). SPI is also the index recommended by WMO for its relative simplicity to calculate. More recently the standardised precipitation evapotranspiration index (SPEI) which also considers losses from evapotranspiration have become more frequently used (Vicente-Serrano et al., 2010).

2.6.3. Operational platforms for alert visualization and dissemination

Available public platforms (at regional, national, and supranational level) are usually focused to drought indicators based on measurements, not even forecasts. Drought impacts data, as mentioned above, is limited and one cannot expect to find real-time records. However, innovation and research are active this field and progress is on-going. The following subsections illustrate with significant examples the status of this matter:

- EDO: Drought indicators at European level.
- Catalan drought viewer: Drought warnings-based water availability in the region of Catalonia.
- ANYWHERE Experience: Prototype multi-hazard platform with forecasts of droughts indicators;

2.6.3.1. European drought observatory

The European drought observatory (EDO) is a service run by the European Commission’s Joint Research Centre. The EDO portal contains drought information, graphs and time-series at European level. These data can be freely downloaded for offline analysis. EDO also provides a tool enabling the comparison between several indicators or the comparison between the values of a same indicator at different times (Figure 11). The monitoring of droughts is based on the analysis of a series of indicators, representing different components of the hydrological cycle (e.g., precipitation, soil moisture, reservoir levels, river flow, groundwater levels) or specific impacts (e.g., vegetation water stress) that are associated with a particular type of drought.

2.6.3.2. Catalan drought viewer

The portal "El visor de la sequera" (The Drought viewer) is an initiative of the Catalan Water Agency (ACA) to let the general population monitor the evolution of the drought in terms of water availability. Over a map of Catalonia, areas consuming water from the same reservoirs (or aquifer) are coloured according to different warning levels.

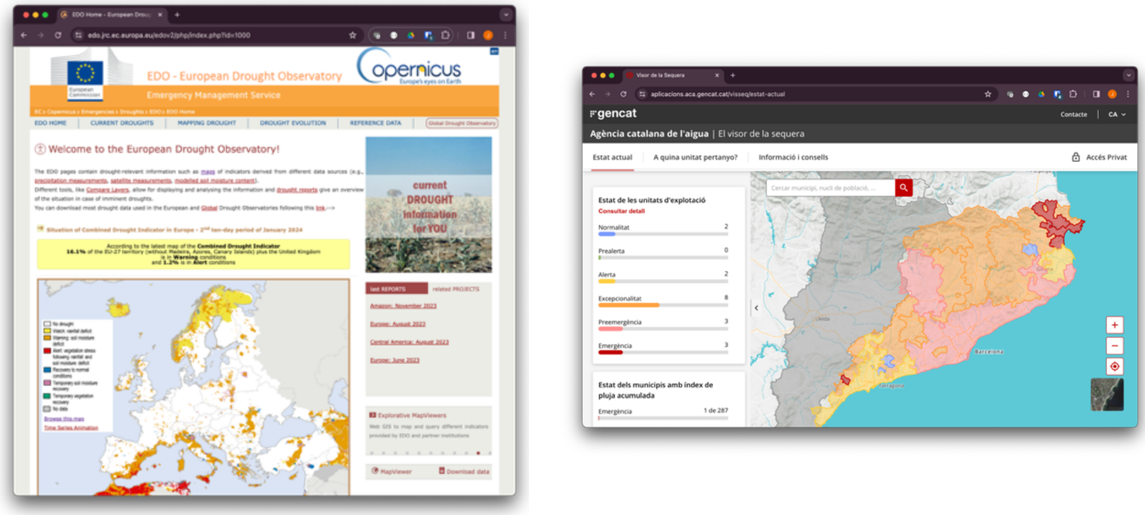


Figure 11 Left: EDO portal Right: Drought View

2.6.3.3. ANYWHERE Experience

In the framework of the H2020 ANYWHERE project researchers at Wageningen University in the Netherlands developed algorithms for drought indicator forecasting based on EFAS and ECWMF long-term hydrometeorological forecasts (Sutanto, van der Weert, et al., 2020; Sutanto, Wetterhall, et al., 2020). Such indicators at European level were integrated and automatically updated in real-time in a prototype platform oriented to civil protection authorities.

2.6.4. End users

ANYWHERE algorithm for SPI calculation is being used in, at least, two operational platforms: one belonging to the Irish Meteorological Service (Met Éireann) and one in the region of Galicia (NW of Spain) by the Water Management authority (Augas de Galicia). For now, there is no work done for translating such indicator forecasts to impact.

The expected end users of the outcomes proposed here are a wide range of authorities (civil protection, water management, meteorological services…), but other end-users may arise from other sectors as agriculture, academia. At least some of the new advancements that are now under research (Boult et al., 2022; Stahl et al., 2016; Sutanto et al., 2019; Westerveld et al., 2021) as the application of machine learning methodologies to impact forecasting, are expected to contribute on the operational side in the near future.

2.6.5. How will GOBEYOND take this to the next level?

The current products in for example EDO provide a lot of different output for drought monitoring, but not many for drought forecasting, especially for forecasting impacts. There is therefore a scope to extend the current products to include forecasting of drought impacts.

In **GOBEYOND**, the algorithms developed in ANYWHERE for drought indicators such as the SPI will be used and further developed to extend the forecast to impact at local level at real time. Such forecasted impacts will be obtained crossing the most recent forecast of the drought indicator with known vulnerable elements (or areas) according to predefined thresholds.

The definition of the vulnerable elements will be co-developed with stake holders and local authorities, using the existing knowledge. Vulnerable elements could be areas highly dependent on precipitation for water availability (human consumptions) or areas with agricultural activity where according to dominant crop and the time of the year impact may be variable.

The ECMWF produces each month a European-scale seasonal weather forecast from the SEA5 model. The forecasts consist of a set of 51 equiprobable members that have a daily time resolution and a 7-month horizon. These forecasts are used as input to the European-scale hydrological model LISFLOOD, run by EFAS with a 5km grid. This produces European-scale hydrological forecasts as output, which are included in the seasonal outlook published by EFAS on a monthly basis.

The SPI will be calculated for each cell of the model grid (LISFLOOD, 5x5 km) for each month of the forecast in each ensemble member. The calculation of the IPE for any grid cell is based on a long precipitation record (in our case 27 years) that is fitted to a probability distribution, which in turn is transformed to a normal distribution so that the mean SPI for the desired location and period is zero.

Vulnerable elements or areas will be crossed against the gridded forecast obtaining an impact forecast according to hyperlocal thresholds.

For such an implementations two data sources need to be available in “real-time”:

- Precipitation forecasts of SEA5 produced by ECWMF
- Precipitation simulations forced with observation (SFO) generated by EFAS

2.7. Fire danger

2.7.1. State-of-the-art and objectives

Fire plays a vital role on earth as both a natural ecological process - shaping landscapes and promoting biodiversity - and a force influencing climate patterns through the release of gases and particles into the atmosphere. Fire is also a global hazard, causing substantial economic losses encompassing damage to infrastructure, reduction of agricultural productivity, increased healthcare expenses due to respiratory issues.

Current systems are based on the prediction of fire danger, which refers to the potential for a fire to develop, spread, and cause damage once an ignition has taken place. Meteorological and fuel conditions in addition to topography all contribute to the overall fire danger in a specific area. Forecasting fire danger relies on the development of physical models able to predict the short and long-term drying of available fuel and how this translates into landscape flammability.

High temperatures, low humidity, and strong winds create an environment conducive to rapid fire spread. The biomass available and its moisture, including vegetation and organic matter, significantly impacts fire intensity and sustainability. Dry and highly combustible fuels increase the risk of ignition and enhance fire spread. Topography also plays a role as slope, aspect, and elevation influence wind patterns and fire spread through increasing fuel contact to flames.

While human activities such as land-use changes and arson contribute significantly to fire activity globally. However, these are not explicitly accounted for in predictive tools used today which mostly rely on weather forcings. However socio-economic data, land-use patterns, and historical fire occurrence are often used to complement the human impact and translate fire hazard forecast into more actionable fire risk.

As wildfires become increasingly prevalent and destructive, the importance of accurate fire danger forecasts cannot be overstated. Advances in meteorology, remote sensing technologies, and predictive modelling empower authorities to anticipate and mitigate the impact of wildfires on communities and ecosystems. Integrating these forecasts into comprehensive natural hazard management strategies is essential for building resilience and minimizing the devastating effects of wildfires on our environment and society.

2.7.2. Principles and elements of theory

To understand the factor influencing fire existence the fire triangle or combustion triangle is a simple model to represent the necessary drivers. The triangle illustrates the three elements a single flame needs to initiate and expand: heat, fuel and oxygen.

When we consider wildland fire, we refer to fires that take place in open landscapes. In this case we can still use the concept of the fire triangle, but it expands to describe the dynamics of fire spread across landscapes and, its recurrence over time (Figure 12). While heat is essential for the ignition of the single flame, topography influences fire spread by preheating upslope fuels. Patterns of recurring ignitions both from human and natural sources play a role in explaining longer-term recurrence. While the availability of oxygen sustains a flame, it is wind that supplies it in a spreading fire. Climate by influencing the longer-term weather pattern controls the changing patterns of fires.

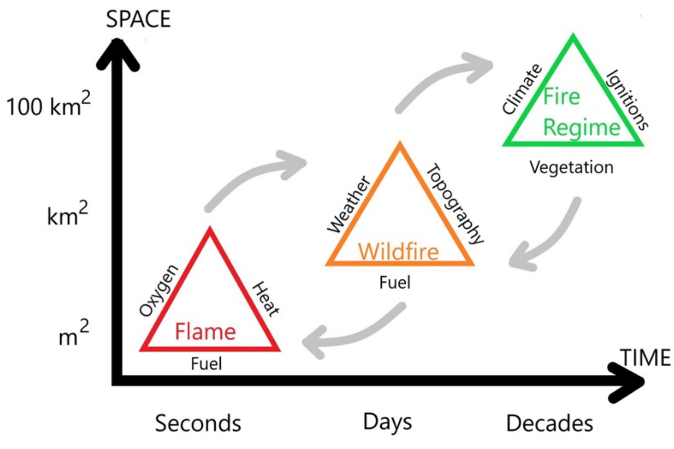


Figure 12 Multi-scale fire triangles describing the elements of wildland fire at the scale of the flame, a wildfire, and a fire regime.

Source: Adapted from Moritz et al., 2005

Fuels, ranging from individual flame combustion to vegetation in spreading wildfires, vary across larger space and time scales. On the smallest scale, the combustion fire triangle depicts the burning of individual fuel particles, releasing energy to the surroundings over seconds to a few days. At the largest scale, the fire regimes are influenced by global climate change, affecting factors such as climate modifications and land use changes. Especially changes in vegetation types can impact the fire regime, altering characteristics such as recurrence, intensity, seasonality, and biological effects associated with specific fire patterns.

2.7.3. Technological requirements

While fire science spans the three different scales identified in Figure 11, the scope and ambition of go-beyond is to improve fire prediction at the daily time scale and to provide operational information in situations of pre-alert, suppression, and limitation (Yellow triangle in figure 11). There are three main tools that are employed at this scope, fire danger forecasting, fire activity real time monitoring and high-resolution simulation of fire propagation and behaviours.

2.7.3.1. Fire danger forecast

Model to predict landscape flammability have been developed by several countries trying to simulate the short and long-term drying of the available fuel. Almost all these fire danger rating systems rely on observed weather data which only allow for daily environmental monitoring of fire conditions. Even when this estimation is enhanced with the combined use of satellite data, such as hot spots for early fire detection, and land cover and fuel conditions, it normally only provides warnings with a four-to-six-hour lead time. By using forecast conditions from advanced numerical weather models, early warning could be extended up to 1-2 weeks allowing for greater coordination of resource-sharing and mobilization within and across countries. This is a direction that has been taken by most countries and a list of available resources is provided in the next session.

Fuel availability and status are often neglected. The reason for this simplification is historical as fire danger models like the fire weather index (FWI) were developed for local applications and often calculated at human-operated stations where weather measurements were collected, and fuel status could be observed (Lawson & Armitage, 2008). This was also at a time when continuous and globally available fuel monitoring was unavailable. Since then, there has been a steady improvement in our monitoring capabilities. Optical sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS) have been collecting the leaf area index (LAI) and the fraction of absorbed photosynthetic active radiation (fPAR) for the last 20 years could be used to monitor fuel status. Similarly microwave sensors have the capabilities to retrieve Vegetation optical depth (VOD). At lower orbiting height unmanned aerial vehicles (UAVs), allow for real-time monitoring of vegetation health and fuel moisture levels. Geographic Information System (GIS) technology could also aid in mapping and analysing the topography of an area, contributing to more accurate fire danger forecasts. Incorporating these factors into predictive models can enhances our understanding of how wildfires may behave in different landscapes.

2.7.3.2. Fire behaviour modelling

The modern quantitative study of surface fire spread began with R. C. Rothermel's semi-empirical rate-of-spread formulation (1972), which relates wind, slope and fuel properties to forward rate of spread and became the conceptual foundation for most operational surface-fire behaviour calculations. research.fs.usda.gov Rothermel's equations have been embedded into widely used operational systems for planning and tactical simulation, for example the FARSITE fire-area simulator and related toolchains, which couple Rothermel-based spread with modules for crown fire, spotting and fire acceleration to produce mapped, time-resolved fire growth scenarios for incident management and planning. Modern toolkits such as Behave/BehavePlus implement the same physics and provide user interfaces and fuel libraries for applied use. US Forest Service+1

To achieve very rapid scenario generation and probabilistic ensembles for operational forecasting, many groups adopted cellular-automaton (CA) paradigms. CA models discretize the landscape into cells and use transition rules, often driven by local wind, slope, fuel and fuel moisture, to propagate fire stochastically. PROPAGATOR (developed by CIMA in Italy) is an example of an operational, stochastic CA designed for rapid ensemble runs and to incorporate spotting, topography and variable fuels for near-real-time risk assessment. CA-based approaches are especially useful for fast scenario exploration and sensitivity/uncertainty analysis where full physics models would be too slow. Across approaches, model performance depends on high-quality inputs: fuel maps, fuel moisture (from in-situ networks or proxies such as LAI, VOD or microwave retrievals), terrain, and temporally resolved wind/meteorology (observations or NWP forecasts). Active-fire detections from thermal sensors (MODIS, VIIRS, geostationary thermal imagers, Sentinel-3 SLSTR) and high-resolution optical data (Landsat, Sentinel-2) are commonly used to initialise ignitions, validate propagation and to guide burned-area detection algorithms that complement spread models (see next point).

Over the past decade there has been rapid growth in data-driven fire-spread models that use machine learning and deep neural networks to learn spatio-temporal propagation directly from historical remote-sensing, topography and meteorological datasets. Recent peer-reviewed studies demonstrate that convolutional and recurrent architectures (e.g., CNNs, ConvLSTM/attention variants, encoder–decoder networks) can forecast next-day or multi-day spread and final burned extent with competitive skill for some regions, especially when trained on large, curated datasets and when wind and vegetation covariates are included. These models are fast at inference time and are being evaluated as complements to physical/CA models for rapid scenario generation and probabilistic forecasting.

2.7.3.3. Detection of fire activity

Fire activity is primarily monitored using two satellite-derived products: active fires (AF) and burned area (BA).

AF indicate the presence of a temporal thermal anomaly within a grid cell. To ensure reliability, AF products exclude permanent or natural heat sources such as gas flares, industrial facilities, or volcanoes, keeping only anomalies linked to actual burning. Each AF pixel records the day of detection (day-of-year, 1–365; 0 for unaffected pixels). Although AF only capture fires burning at the time of satellite overpass, they are fundamental for tracking the extent, intensity, and temporal dynamics of wildfires. AF data are widely used to analyse fire regimes, estimate rates of spread, emissions, and guide BA algorithms by distinguishing true fire signals from other surface changes.

Historically, AF detection began with NOAA-AVHRR and ERS-ATSR, but accuracy improved with MODIS, the most widely used system for the last two decades. Additional sensors include geostationary satellites, VIIRS onboard NOAA polar satellites, SLSTR on Sentinel-3, and Landsat-OLI, albeit with lower temporal frequency. Early optical systems such as DMSP-OLS detected night-time fires via radiance contrast Spatial resolution ranges from 30 m (Landsat, FireBird) to 4 km (geostationary), offering complementary capabilities for near-real-time detection and long-term monitoring.

BA quantifies the total surface affected by fire, identifying pixels as burned when most of their area contains burned vegetation. BA can be expressed as total area (m^2) or as the day of first detection. Unlike AF, BA represents the complete extent of fire-affected zones and is essential for assessing global fire impacts. Detection challenges remain for low-severity, under-canopy, or small cropland fires with weak spectral contrast.

BA datasets underpin analyses of fire regimes, extreme events, deforestation, albedo, ice, and hydrological changes, and are central to risk assessment, model verification, and emission estimation. The most widely used products are MODIS-based: NASA's MCD64A1 (500 m) and ESA's FireCCI51 (250 m). Both rely on AF detections to guide burned-pixel identification. With MODIS nearing its end of life, new BA products are being generated from Sentinel-3 SYN and VIIRS, maintaining continuity in global monitoring. Advances in cloud computing now enable high-resolution BA mapping from Landsat and Sentinel-2 MSI revealing substantial differences in burned area and emissions compared to coarse-resolution products.

2.7.4. Operational platforms for alert visualization and dissemination

Due to the improved skills of weather forecasting, the use of NWP has offered in recent years a real opportunity to enhance early warning capabilities (see Table 1 for an overview). Institutions such as Natural Resources Canada (NRC) and the US National Oceanic and Atmospheric Administration (NOAA) have implemented regional fire danger forecasting systems based on their operational weather forecasts. NASA's Fire Information for Resource Management System (FIRMS) is a satellite-based platform that monitors and provides real-time information on global fire activity. Using data from sensors like MODIS and VIIRS, FIRMS enables users to track active fires, assess their impact, and support effective wildfire management. The Global Fire Early Warning System is also an international initiative, promoted by the Canadian Partnership for Wildland Fire Science and the United Nation Office for Disaster Risk Reduction, to provide fire danger forecast up to 10 days ahead using the Canadian operational weather forecasting system. Parallel initiatives are promoted by the European Commission under the umbrella of the Copernicus Emergency Management Service (CEMS), namely the European Fire Forecast Information System (EFFIS) and its global counterpart the Global Wildfire Information System (GWIS). Both systems principally rely on the Canadian Fire Weather Index (FWI) to rate fire danger and on numerical weather predictions to provide forecast fire danger information at the European and global levels. In terms of fire behaviour modelling *Rothermel-based physics* remains the backbone where mechanistic interpretation and fuel-specific behaviour are required (planning, fuel-treatment evaluation and scientific studies *Deterministic simulators* (e.g., FARSITE / BehavePlus) remain in operational toolboxes for incident modelling and post-event reconstruction *Cellular automata* (e.g., PROPAGATOR) provide rapid stochastic ensembles and operational forecasting when speed and scenario exploration matter AI/deep models are emerging as complementary tools that can learn complex spread patterns from multimodal inputs and offer very fast forecasts, but they require large labelled datasets and careful evaluation before replacing physics-based predictions in operational decision chains.

Table 1 Examples of operationally forest fire early warning systems.

System	Institute	Coverage	Link
Canadian Wildland Fire Information System	Natural Resources Canada	Canada	https://cwfis.cfs.nrcan.gc.ca/maps/fw
Natural Weather service	US National Oceanic and Atmospheric Administration (NOAA)	North America	https://www.weather.gov/fire/
Fire Information for Resource Management System (FIRMS)	National Aeronautics and Space Administration (NASA)	Global	https://www.earthdata.nasa.gov/learn/find-data/near-real-time/firms
Global fire monitoring center (GFMC)	United Nation Office for Disaster Risk Reduction (UNDRR)	Global	https://gfmc.online/
European Fire Forecast Information System (EFFIS)	Copernicus Emergency Management Service (CEMS	Europe	https://effis.jrc.ec.europa.eu/
Global Wildfire Information System (GWIS)	Copernicus Emergency Management Service (CEMS	Global	https://gwis.jrc.ec.europa.eu/

2.7.5. Validation

Weather forecast provides skilful information to derive fire weather indices values up to 10 days ahead and high fire danger values correlate with global burned areas (Abatzoglou et al., 2019; Di Giuseppe et al., 2020). Predictive skills could extend also beyond the provided forecast range. Similarly, to other sectoral applications there is scope to extend the prediction to the sub-seasonal and seasonal time frame (S2S; Bedia et al., 2018). Still, there are serious limitation and a good skill in forecasting FWI values do not translate into a satisfactory probability of detection for real fire events. Fires in Boreal regions for which the FWI has been calibrated display a probability of detection above 50% (Di Giuseppe et al., 2016). Mid and high latitude forested areas, where fuel is abundant have the highest predictability while in savanna and shrub-land regions the relationship between FWI and fire occurrence weakens.

Looking at large fire events in the recent past there are regional differences and in semi-arid regions like Portugal and California the fire danger forecast based on FWI can be accurate up to 10 days ahead. Another interesting aspect attached to the use of weather forecasts is the use of probabilistic information. The quantification of forecast uncertainties using ensemble predictions is something still new in fire forecasting. However, it opens great opportunities in terms of adding a confidence level to the fire prediction.

2.7.6. How will GOBEYOND take this to the next level?

GOBEYOND will focus on improving fire danger forecasting. For years, fire danger rating systems have been a cornerstone of fire management agencies' tools to pre-emptively identify critical areas. Among others, the FWI is widely used thanks to its ease of implementation (de Groot et al., 2007) and its correlation with fire activity in forested areas. Still, several studies have highlighted the limited performances of this and similar metrics in fuel-limited ecosystems where fire is driven by the short-term superficial drying of intermittently available biomass. Not accounting for the actual fuel available for burning is one of the most important limitations that hinder the meaningful usability of the FWI in savanna-type ecosystems (Di Giuseppe et al., 2020).

Furthermore, interpretation of FWI values is domain specific as it does not directly translate into the probability of fire. The complexity in the relationship between vegetation and fire occurrence makes probabilistic wildfire occurrence difficult to describe using process-based modelling. Recently, the use of data driven methods has emerged as an option to overcome the complexity of describing the underlying processes (G. Zhang et al., 2021; Zhu et al., 2022). Data-driven methods are effective when required input observations are available. New indices have been proposed recently, such as the fire occurrence probability index and the probability of fire (PoF) to overcomes part of the limitations that characterise the FWI (Di Giuseppe, 2023). There are two innovative aspects in these new indices. The first aspect is that, by combining fire danger information with information on vegetation characteristics, they provide a framework to account for real-time fuel availability. As an immediate benefit, they limit unrealistic high values registered in desert areas where fire activity is hindered. They also allow us to retain a memory of previous burning before vegetation recovery takes place. The second advantageous aspect is that they express a probability of fire occurrence based on previous observations. By explicitly considering the burning history of a given landscape, they allow for landscape susceptibility to be considered.

AI-derived indices can outperform the FWI in many situations and in fuel-limited ecosystems they pose the bases of a paradigm shift in fire danger forecast. As more variables become available for forecast input in the future, e.g., prognostic LAI, model skill is expected to further improve, as currently input variables limit the skill at longer lead times. Furthermore, the addition of input variables that control ignition, whether human or lightning activity, are expected to further improve model skill. Currently, variables directly correlated with fire activity have been used as input to the model; however, it is feasible that by performing regional or grid point specific training will result in improved model performance by indirectly representing processes not included in our input.

There are currently no systems that explicitly that calculates the risk given a specific fire hazard. Some systems, like EFFIS, allows for overlaying with population, ecological and economic vulnerability in a wild risk viewer. However, the viewer is not calculating the risk in terms of hazard combined with exposure and vulnerability, so it cannot be said to be the true fire risk.

3. Methodologies and technologies for enhancing response capacity in Geo events

The geo hazards that are described in this section are earthquakes, volcanoes, tsunami and landslides. For each risk, several different methods are illustrated along with their level of maturity for social use, technological requirements, end-users, advantages and limitations that are evident upon their current applications in Europe and worldwide.

3.1. Earthquakes

An earthquake is a natural hazard resulting from the sudden release of fracture and wave radiation energy, mostly occurring within the brittle Earth's crust, leading to seismic waves that propagate to the surface and cause strong ground shaking. The seismic wave shaking can result in a range of destructive effects depending on factors such as the earthquake's magnitude, depth, distance from populated areas, and local geology. In this project we will consider methodologies for both earthquake early warning and in support for rapid response strategies.

Earthquake Early Warning (EEW) systems are real-time seismic monitoring infrastructures aimed at issuing an alert and activating emergency safety measures to protect people, buildings, and industrial facilities in advance of the impact of strong and potentially damaging shaking waves. The basic principle on which network-based EEW systems ground on, is to maximize and exploit the time lag between the alert message issuance and the arrival of damaging seismic waves, by broadcasting an alert soon after the first P-waves are detected at a near-source deployed, seismic network. In the aftermath of the earthquake occurrence rapid response strategies are essential for effectively managing the immediate emergency of an earthquake and minimizing its impact on lives, infrastructure, and communities. In support to the decision during the rapid response phase following the earthquake, the illustrated methodologies aim at assessing the impact of the earthquake through the fast calculation of the expected ground shaking map and to estimate the potential damage in terms of human life and economical losses, based on the prior knowledge of on the building estate and population in the region affected by the earthquake shaking.

3.1.1. Earthquake early warning systems

EEW systems are designed to detect seismic waves generated by earthquakes and provide advance warning to populations before the shaking reaches them. Network-based EEW systems analyse the early P-wave signals recorded at the stations, detect the occurrence of the earthquake, determine its location and magnitude, and estimate its shaking potential at nearby and distant sites, using previously calibrated empirical attenuation relationships (ground motion prediction equations, GMPE). Onsite or stand-alone early warning systems use a single station, or small-aperture arrays of sensors deployed in proximity of the target site to secure. In this case, the measures of the initial P-wave amplitude and/or the dominant signal frequency can be used as proxies for the late arriving, strongest shaking wave amplitudes at the same site, with no need for information on the earthquake location and magnitude. In this chapter we will describe two network-based and two onsite methodologies that reproduce the basic features of all commonly adopted EWS. All methodologies base their alert on the strong ground shaking prediction at the area of interest, that changes from the local scale for onsite systems to the regional and nation-wide scale for the network-based systems. In the following paragraphs we will introduce and discuss two methodologies for network-based EEW (source PRESTo, and impact based QUAKEUP) and two (SAVE and P-Alert) onsite methodologies both aimed at the earthquake impact prediction in terms of expected strong ground shaking.

3.1.1.1. PRESTo – Source -based impact estimates

State-of-the-art and objectives

PRESTo is a network-based early warning system that rapidly estimates the location and magnitude of an earthquake, while the earthquake is still occurring (Figure 13). It uses the early P-wave signal and (where already available) the early S-wave signal recorded at the accelerometric and velocimetric stations of a dense seismic network deployed in the epicentral area. The system then predicts the peak ground shaking produced at the regional level, using a point-source approximation and ground motion prediction equations. The approach is time-evolutive and probabilistic for both the source parameters estimation (location and magnitude) and the estimation of the earthquake impact (peak ground acceleration or velocity). Alert messages with the time evolutive source parameters are broadcast to a dynamic set of users in the region through a central server, while the expected impact and lead-time is continually and directly sent to specific target sites. This allows for the rapid initiation of automatic safety actions at critical infrastructures up to several tens of seconds before the arrival of the damaging waves, and likewise can direct the public at large, in the effectively affected areas, to perform individual actions (duck-and-cover) to mitigate collateral damages.

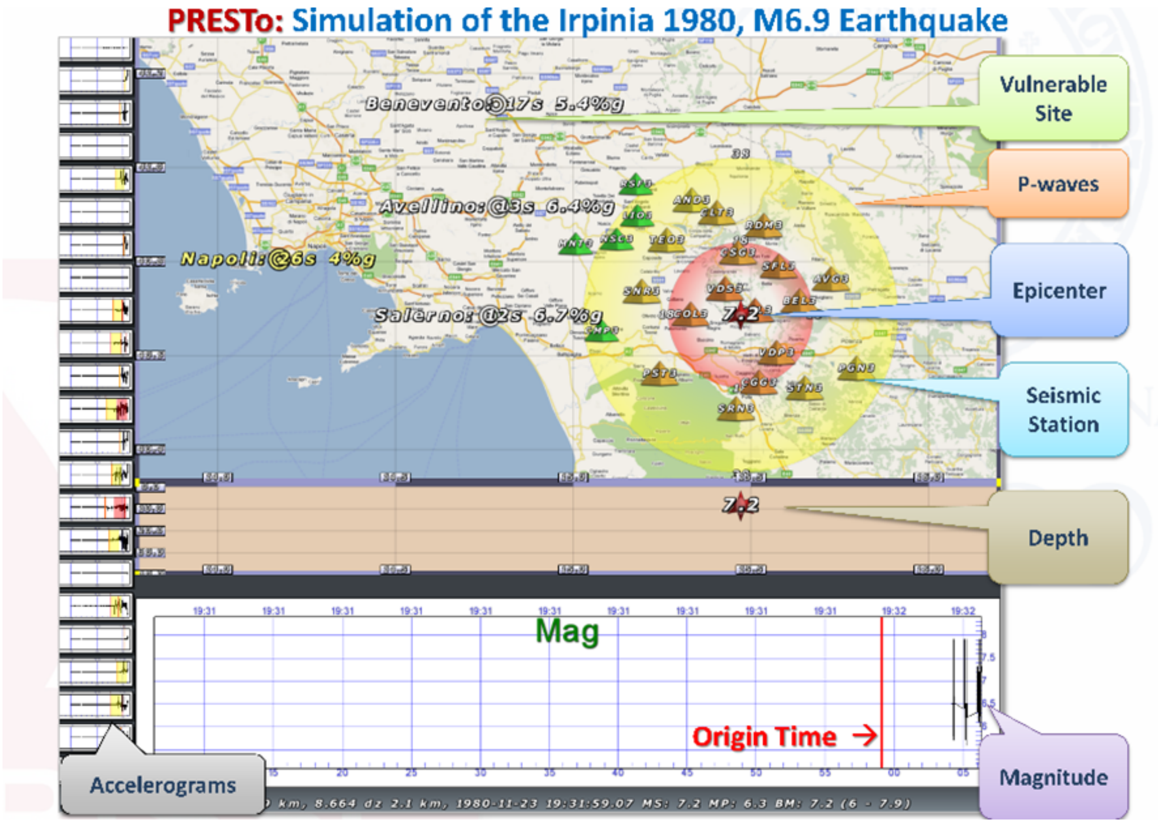


Figure 13 Screenshot of PRESTo during the playback of synthetic waveforms for the 1980 M6.9 Irpinia earthquake.

The target site in Naples receives the first alert (PGA = 4 %g) with 26 seconds of pre-alert.

Principles and elements of theory

The processing starts from the real-time streaming of ground acceleration or velocity waveforms from the stations (SeedLink); P-wave phase picking is performed on each station (FilterPicker); the earthquake detection is based on the spatial-temporal associations of the picks at a minimum number of stations; the probabilistic earthquake location is based on the differential arrival times at triggered and not-yet-triggered stations (RTLoc); The Bayesian magnitude estimation uses the peak displacement measured on short-time windows (2-4 s) of P- and S-wave signals at each station and the distance to the hypocenter (RTMag); The impact prediction and alert message is based on the estimation of PGA and/or PGV at the regional level from magnitude and location (GMPEs). All of the output parameters are provided with their uncertainties, stemming from the probabilistic approach and from the uncertainties of the empirical relations being used. In a dense seismic network (average inter-station distance of around 15 km) around the epicentral area, magnitudes above 2 and depths around 10 km, typically the system produces a first alert with estimation of source parameters and impact prediction at the regional scale within 4-6 seconds from the first arrival at a station and cuts down the uncertainties within 10 seconds.

Technological requirements

A dense seismic network must be deployed in the epicentral area, with a radius of the order of 50-100 km and an average inter-station distance below 20 km. Strong-motion accelerometers are preferable, to avoid saturation in case of moderate to large earthquakes. Real-time data transmission through the SeedLink protocol is required, either directly from the stations, or through data collection servers. The possibility for the stations to transmit 1-second data packets (or less) of ground motion in a controlled fashion is preferrable, in order to minimize latency and thus reducing the lead-times. The hardware requirements for the server running PRESTo itself are modest, e.g., a 3 GHz 8-core Xeon class CPU, 16 GB of RAM and a discrete GPU, using either Windows Server or Ubuntu as OS, is adequate for a network of 100-150 km of radius and 30-50 stations. The hardware requirements obviously grow with the number of stations, the geographic extent of the network, as well as the required precision of the location and the desired frequency of the alert updates. Processing and alert dissemination is fully automatic and requires a receiving server/device at the target site with a public IP and/or a server for the dissemination of the broadcast alerts (e.g., ActiveMQ).

Operational platforms for alert visualization and dissemination

The system includes a built-in GUI for the real-time visualization of incoming data (i.e., real-time waveforms from the stations), detected earthquake (i.e., location on a map, magnitude graph) and its impact (predicted PGA and lead time at target sites on the map). Specific alert messages are sent at least every second directly to the (public) IP of all the target sites known to the system, as short text messages containing all the evolutive earthquake parameters and the target-specific predicted ground shaking (PGA, PGV) and lead-time. This requires a target-installed device or software to further process the alert and to eventually act through application-specific actuators. Additionally, a regional alert message, in QuakeML format, is sent to a server (broker) for broadcast dissemination, using the STOMP protocol, which requires the installation of e.g., an ActiveMQ server. In this latter case the clients for the broadcast message only receive the earthquake parameters and will have to compute the expected shaking based on the predicted earthquake parameters and their current distance to the source (e.g., through GMPEs). Two such clients exist: The Earthquake Early Warning Display (open source) for fixed position targets, and an App for mobile phones (SISMUp, in development by UNINA) for individual people in dynamic locations acquired through GPS or Wi-Fi proximity. Additionally, a summary e-mail of the earthquake location and magnitude is sent to a mailing list at the end of the earthquake processing (~15 seconds from the earthquake detection).

Real-time and offline actual use

PRESTo is running continuously since 2009 on the real-time data streams of the ISNet network (31 accelerometric stations) located in the Irpinia region (southern Italy), providing its alert to the seismologic laboratory of the University “Federico II” of Naples. Since 2016, within the EPOS project, it provides a public bulletin of its real-time alerts compared to the official ISNet and INGV bulletins, within CREW – the EU Testing Center for Earthquake Early Warning and Source Characterization (https://lccepos.fisica.unina.it). PRESTo is one component of the EW system running in real-time in Romania (Vrancea region) on the RoNet network (Romanian Seismic Network - National Institute of Research and Development for Earth Physics), which also sends alerts to the public. It is under real-time experimentation in South Korea at KIGAM on the whole national seismic network. In Turkey it is under real-time experimentation on stations from the KOERI network (Kandilli Observatory and Earthquake Research Institute) surrounding the Marmara region. An off-line feasibility study and configuration have been published for the eastern central Italy area and the real-time experimentation on the same area, using the INGV network, is ongoing.

End Users

Academic institutions and local authorities can be automatically alerted in real-time of the occurrence of an earthquake and of its impact at the regional level, up to several tens of seconds before the arrival of the damaging waves. Individual target sites such as schools and sensitive infrastructures have the possibility to visually display the most important information (distance to the source, magnitude, expected intensity at their site and a spoken count-down to the start of strong shaking) through client applications. Automatic safety measures can be initiated upon receiving these alert messages by custom devices installed at the target sites, based on specific cost-benefit criteria, considering the uncertainties, provided in the message. The public at large through a mobile App can be similarly alerted and guided to perform safety actions. The possibility to also provide through the App personal feedback on the experienced shaking/damage and well-being in the immediate post-event, could further facilitate the rapid response from central authorities.

Pros and cons of the methodology

Cons: the performance of the system in strongly dependent on the correctness of the source parameter estimation which can be affected by noisy environments and seismic network failures. Also, the ground motion prediction equations in a point-source approximation can only provide rather uncertain and geometrically simplified impact estimations. The system configuration is region-specific, and it thus requires an initial phase of calibration of the regression laws, optimization of the software parameters and off-line, as well as real-time testing and optimization, of the order of a year.

Pros: the relative simplicity of the approach and long-running real-time testing of the software in different geographic areas and network configurations, allows to expect predictable and controlled performances on already tested or new areas. The ease of use and ease of deployment of the software makes it possible to integrate Early Warning capabilities to an existing seismic network and geographic area with minimal effort, both in terms of alert production and alert dissemination to specific end-users and, potentially, the public at large. Provided, of course, that the technological requirements are met (network geometry, telemetry performance). The software has a built-in waveforms playback functionality to simulate the real-time behaviour, making it easier to tune the parameters and regression laws.

3.1.1.2. QUAKEUp – Impact (shaking-forecast)-based Early Warning System

State-of-the-art and objectives

QuakeUp is an impact-based earthquake early warning system that can identify an ongoing seismic event and estimate the impact of this event in the surrounding area in terms of peak ground velocity (PGV), acceleration (PGA) and instrumental intensity. This estimation is performed using both regional ground motion prediction equations (GMPE) and onsite P-wave amplitude measurements. When a seismic station of a dense network deployed in the epicentral area is reached by the early P-wave radiated by the earthquake, the real-time measurements of P-wave acceleration, velocity and displacement are performed and used to predict (through previously calibrated empirical relations) the PGV at the site and in not-instrumented sites the Ground Motion Prediction Equation (GMPE) are used in combination with PGV predictions at seismic stations. Using a physics-based interpolation method, the onsite and GMPE predictions of PGV are combined to obtain a real-time evolutive shaking-forecast map of the earthquake potential damage area. In this approach the alert is broadcasted to users (population, strategic infrastructures, industrial plants) located in the area surrounding the earthquake epicentre where the ground shaking is expected to exceed a user-set threshold.

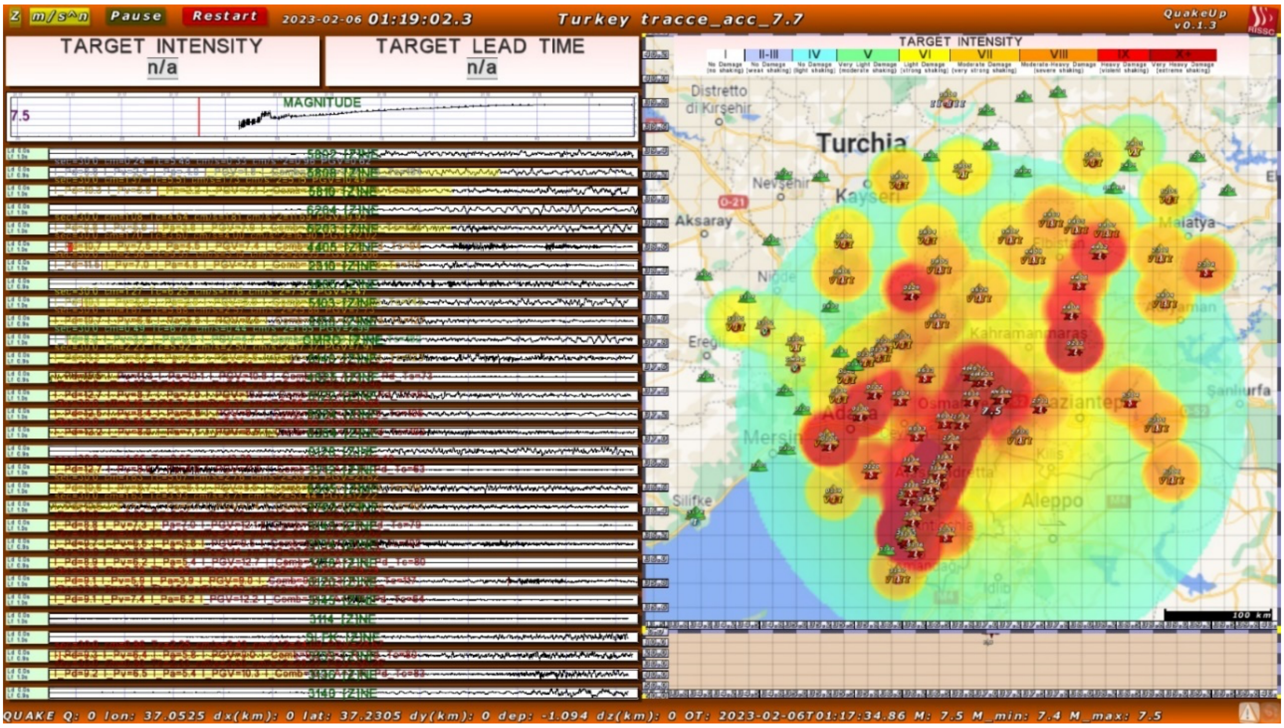


Figure 14 Retrospective application of QuakeUp to the strong motion records of the M 7.8 Turkey-Syria earthquake occurred on February 6, 2023.

The left panel shows the real-time waveform data streaming from the stations, while the right panel displays the real time predicted shaking-forecast map with the epicentral position estimation. The top-left and bottom-right panels show the time evolution of the earthquake magnitude and depth.

Principles and elements of theory

The algorithm is designed to process in real-time the seismic records of an ongoing earthquake as soon as it is identified by a minimum number of stations that can be set by the user. An automatic picker module (FilterPicker) identifies the first P-wave arrival and the system starts to estimate the event location and the magnitude using the time and amplitude of the early P-signal. The location procedures are performed using a real-time earthquake location method, that utilizes both triggered and non-triggered stations. The magnitude estimation, instead, is based on empirical attenuation laws that correlate the measured P-wave amplitude to the event magnitude and hypocentral distance.

The system predicts the peak ground motion in the region of interest using two different approaches, one for the recording sites and another for the virtual nodes, that is, the not-instrumented grid nodes. Specifically, the PGV at the recording sites is predicted from the recorded P-amplitudes of the early P-wave signals using onsite calibrated relationships. The PGV at the virtual nodes is instead predicted through a physics-based interpolation technique, which uses the available regional GMPE and real-time estimates of earthquake location and magnitude (network-based approach). At each time after the first P-wave signal detected by the seismic network, the system updates the estimates of location and magnitude and recomputes the evolutive shaking-forecast map, that is used to issue an alert when the predicted peak ground motion amplitude exceeds a user-set threshold.

Technological requirements

The method grounds on the existence of a dense seismic network with real-time capabilities of data transmission. Transmission latencies smaller than 1 sec and a limited time windows of data absence should be achieved to minimize latency and thus improve the lead-times. The sensors at the stations of this network could be both accelerometers and velocimeters, but accelerometers are preferred since they guarantee that the recorded signals are not saturated in case of very strong ground shaking, possibly caused near-source by moderate to large earthquakes. The real-time data from these sensors must be transmitted through the SeedLink protocol to a server running the software, for processing and alerts dissemination. Currently only Windows as OS is supported, but a Linux version is in the works. The hardware requirements for the server are modest, e.g., a 4 GHz 8-core Xeon class CPU, 16 GB of RAM and a discrete GPU, using e.g., Windows Server, is adequate for a network of 100-150 km of radius and 30-50 stations. The hardware requirements obviously grow with number of stations, geographic extent of the network, required precision of the location, required density of the shaking-forecast map interpolation and desired frequency of the alert updates. Processing and alert dissemination is fully automatic and requires a receiving server or device at the target site with a public IP or a server for the dissemination of the broadcast alerts (e.g., ActiveMQ).

Operational platforms for alert visualization and dissemination

Currently a visual-display interface (built in the system) is implemented (Figure 14). It shows the incoming waveforms as well as all the estimations in terms of source location/magnitude and impact predictions (PGV, Macroseismic Instrumental Intensity). Concerning alerts dissemination, target-specific alert messages are sent at least every second directly to the (public) IP of all the target sites known to the system. The alert is a short text message containing all the evolutive earthquake parameters, as well as the target-specific and lead-time and ground shaking (PGV) predicted through the physics-based interpolation of regional and on-site ground shaking prediction/measures. A target-installed device or software is expected to further process the alert and to eventually act through application-specific actuators. Additionally, a regional alert message, in QuakeML format, is sent to a server (broker) for broadcast dissemination, using the STOMP protocol, which requires the installation of e.g., an ActiveMQ server. Finally, a summary e-mail of the earthquake location and magnitude is sent to a mailing list at the end of the earthquake processing. QuakeUp is currently in a testing phase at the RISSC laboratory of the University of Naples Federico II. It will be soon installed as a real-time early warning module of the Irpinia Seismic Network.

Real-time and offline actual use

The method is tested only in offline, retrospective applications and analyses. In all these applications a simulation of real-time scenarios has been performed, using networks and data from different seismic regions in the Euro-Mediterranean area.

End Users

This system can be used by national and local authorities and scientific institutions to predict the potential damage zone produced by an earthquake and to provide warning to the population based on this info. The system can be interfaced with automatic control systems to activate emergency safety actions in strategic building or infrastructure or sending an alert message directly to the population, through cellular phones or other information broadcast systems.

Pros and cons of the methodology

Pros: The system can perform both onsite and GMPE- based predictions, which means we can combine the source- and wave propagation- based approaches for seismic early warning. If we consider a site far from the source, we can have the alert based on the GMPE prediction, but we can also wait for an onsite prediction to have a more precise PGV estimation. The impact prediction is based on the P-waves, and this can give good performance in term of quickness.

Cons: To achieve optimal results, we need a dense spatially distributed sensor network located both in the site we want to protect and near the earthquake source. The data transmission and communication system must be capable to run in real-time with a deadline of less than 1 sec. Both for automatic and individual emergency actions, the efficiency and performance of the systems depend on training and education of the end-users.

3.1.1.3. SAVE - On-Site Alert Level System

State-of-the-art and objectives

Nowadays EEW systems are either operational, in phase of implementation or under development in a large number of countries all over the world. Particularly, regional EEW systems integrate a dense seismic array deployed near a seismic source and can issue alerts after a rapid estimation of earthquake location and magnitude.

On-site EEW systems are based on a single sensor, or on a very small array of sensors, deployed directly at the target buildings, infrastructures, or industrial plants to protect. The alert is issued with the info about the expected ground shaking at the target, based on the actual signal recorded at the target itself. This onsite configuration is very useful especially for those areas, like southern Italy, where a lot of infrastructures are located very close to active seismic faults. Here we describe the on-Site Alert leVEl (SAVE) method for early warning system.

Principles and elements of theory

The output of SAVE consists in an alert message about the expected intensity at the site of interest, the magnitude range, and the distance range of the source to the site of interest. The output is declared through a threshold-based method that considers the information coming from the P-wave onset within a maximum P-time window of 3 seconds starting from the first detected P-wave arrival. The Lead Time (LT) is computed as the difference between the arrival time of the maximum shaking amplitude and the warning time. LT may vary depending on event-to-station distances. For Italy, where SAVE has been first calibrated and tested, LT goes from 3 seconds at distances of 20 km up to 7-8 seconds at distances of 40 km.

Technological requirements

SAVE can be installed on a single station that has to provide continuous accelerometric records in time. The data are processed automatically, but off-line performances can be evaluated as soon as waveforms are available. Data transmission is currently issued as a visual alert message on a screen connected to the station. The possibility to issue the alert through text messages on telephones or emails is still under testing.

Operational platforms for alert visualization and dissemination

SAVE is installed and running on three stations of the Irpinia Seismic Network (ISNet). The alert is visualized as a message on a computer screen showing real time streaming of data in the computer room of RISSC Lab at the University of Naples (Figure 15). Since SAVE is still under testing, no protocols for alert dissemination exist currently. RISSC Lab is the academic agency that is responsible for the management of SAVE.

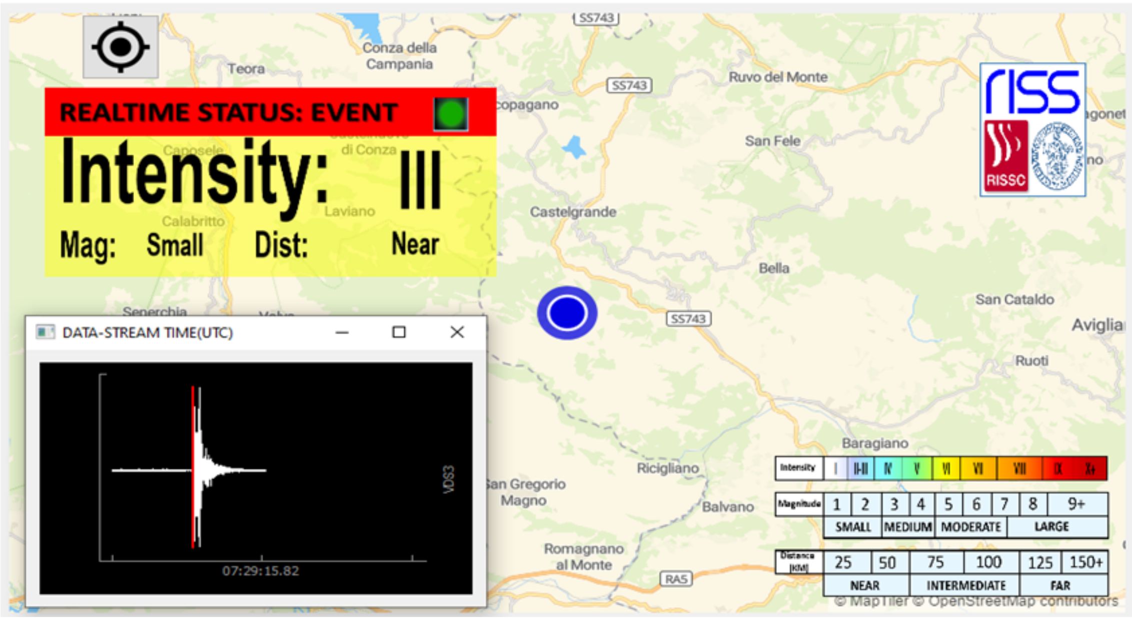


Figure 15 SAVE output after 3 seconds since the P-wave arrival at the closest station to the event epicentre. The seismic station is at 6 km from earthquake location.

Real-time and offline actual use

Both real-time and offline use of SAVE are being performed on ISNET accelerometric data to monitor seismicity in the Irpinia region in southern Italy. Since in the past this region has experienced very strong earthquakes, the on-site system SAVE could be a useful tool to issue fast alerts for the area.

End Users

SAVE can have a very wide range of end users. It can be used for academic purposes (retrospective, off-line analysis); it can be used by local authorities and civil protection so that fast interventions are arranged. It can be used in factories so that dangerous procedures can be shut down before strong shakings arrive at the site. Moreover, it can be used by the large population if alert messages provided by SAVE are sent through notifications on cell phones.

Pros and cons of the methodology

The advantage of SAVE relies on the hidden simplicity of its use: the intensity measure is always provided through the algorithm, and it is the main parameter of interest to issue the alert by whoever the end user is. The potential problem might rely on the issue of false or missed alarms, which is why SAVE requires a phase of offline calibration to set proper thresholds. **GOBEYOND** will surely provide scientific advice, technical expertise, and data expansions so that SAVE will take off as fully operating on-site system on the whole national Italian territory.

3.1.1.4. P-alert - P-wave based alert system

State-of-the-art and objectives

EWSs are real-time, seismic monitoring systems able to detect an ongoing earthquake and provide a warning to a target area before the arrival of the most destructive waves. In a regional EEWS the seismic network is located nearby the source area, while target sites to be alerted are far away from it. In this configuration, the relevant source parameters (event location and magnitude) are estimated from the early portion of recorded signals and are used to predict the expected ground shaking (peak ground velocity, PGV, and peak ground acceleration, PGA) at the target sites through empirical ground motion prediction equations. The on-site configuration consists of a single sensor or of an array of sensors deployed in the proximity of the target structure to be alerted. Here the initial P-wave motion recordings are used to predict the ensuing peak ground motion at the same site, without necessarily estimating the earthquake location and magnitude.

Here we describe a P-wave-based, on-site earthquake early warning system (called P-alert), based on the real-time, continuous measurement of three peak amplitude parameters and their empirical combination to predict the ensuing peak ground velocity. The observed parameters are compared to threshold values and converted into a single, dimensionless variable. A local alert level is issued as soon as the empirical combination exceeds a given threshold.

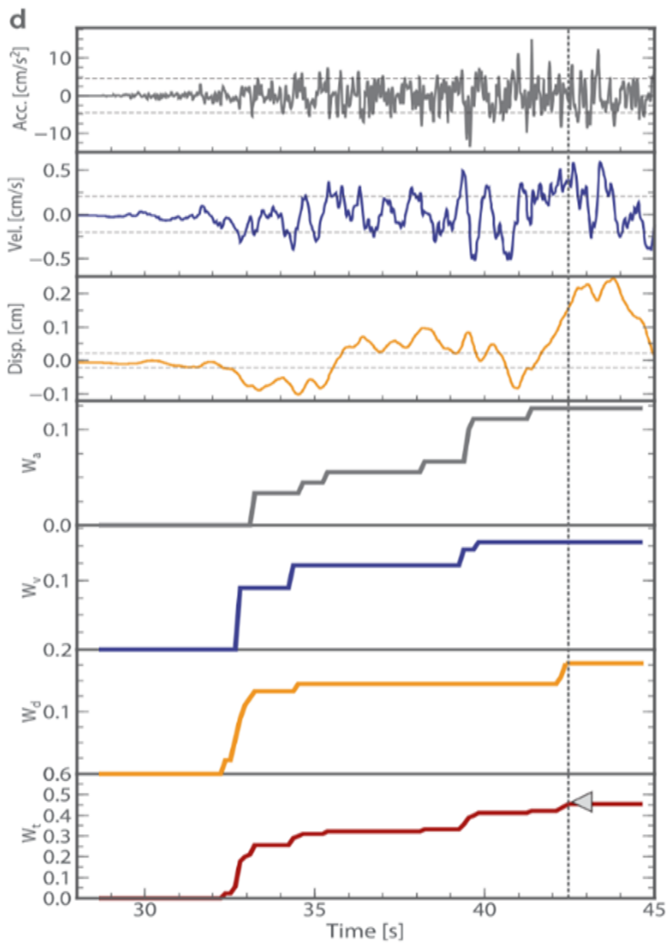
Principles and elements of theory

The P-alert methodology described here is essentially based on two key elements. The first one is the continuous measurement of three peak amplitude parameters (the initial peak of displacement, Pd, velocity, Pv, and acceleration, Pa) on the vertical component of ground motion recordings. Following the concept of the expanded P-wave time window (PTW), the real-time measurements are here progressively performed starting from the P-wave onset and continuously updated as long as the ground motion is recorded. The second key element of the proposed methodology is the use of an empirical combination of the three ground motion parameters for predicting the ensuing PGV at the same site.

At each time along the seismogram, we measure Pd, Pv, and Pa on the vertical component of ground motion recordings and associate them with a fuzzy variable, which is finally used for warning declaration. In this way, the three ground motion quantities equally contribute to the final shaking prediction. The warning is issued as soon as the predicted shaking exceeds a prior established threshold. The methodology provides the expected intensity at each recording station.

Technological requirements

The methodology can be made operative on each single station that provides continuous accelerometric recordings and that is able to transmit real-time data to a local machine, where the software is installed. Real-time data transmission through the SeedLink protocol is required, either directly from the stations, or through data collection servers. The possibility for the stations to transmit 1-second data packets (or less) of ground motion in a controlled fashion is preferrable, in order to minimize latency and thus reducing the lead-times. Off-line performances during an earthquake can be evaluated as soon as waveforms are available. The possibility to issue the alert through text messages on telephones or emails is still under testing. The hardware requirements for the server running P-alert itself are modest, e.g., a 3 GHz 8-core Xeon class CPU, 16 GB of RAM and a discrete GPU, using either Windows Server or Ubuntu as OS). Processing and alert dissemination is fully automatic and requires a receiving server/device at the target site with a public IP and/or a server for the dissemination of the broadcast alerts (e.g., ActiveMQ).



The initial peak amplitude parameters Pd, Pv, and Pa are measured as the absolute maximum of displacement waveform on the early portion of the P-wave.

The threshold values (for the intensity IMM= V) on each parameter are schematically shown as a black, dashed line on each record.

Examples of Wa, Wv, and Wd as a function of time are also shown with a solid black, blue, and orange lines, respectively.
The combined fuzzy variable is shown as a red line.

Figure 16 Example of the vertical component of acceleration (black), velocity (blue), and displacement (orange) signals.

Operational platforms for alert visualization and dissemination

We are currently working on the development of an operational platform that could be easily installed and put in operation at single stations. The platform will allow for alert visualization and issuing. There are no current protocols for alert dissemination and the methodology is under testing offline using data recorded at the Irpinia seismic network.

End Users

Individual stations where the methodology is running will display the expected intensity at their site (Figure 16). Automatic safety measures can be initiated upon receiving these alert messages by custom devices installed at site. Academic institutions can be automatically alerted in real-time of the occurrence of a relevant earthquake, expected to produce large shaking at the station.

Pros and cons of the methodology

The combination of three different parameters provides a broader insight into the ongoing phenomena, while keeping the methodology as simple as possible. Compared with the standard on-site methodologies, this approach is likely to provide reliable warnings and more robust prediction of potential earthquake damaging effects. In the proposed approach, the initial amplitude parameters are continuously measured on the ground motion recordings and the use of limited P-wave windows has been replaced by expanded PTWs. The possibility of expanding the observation time window allows for capturing longer portions of the rupture process and lower frequencies radiated from the source, thus possibly avoiding the earthquake magnitude underestimation.

In practice, a possible risk when expanding the PTW is the inclusion of S-waves, whose amplitude, if not properly considered, may lead to an overestimation of the predicted ground shaking level. The use of the vertical component of ground motion recordings, in principle, minimizes the S-wave contamination on the P-wave amplitude measurement.

3.1.2. Earthquake rapid response

Immediately following an earthquake, the rapid impact assessment is a task priority: immediately sizing up the global consequences of the event is essential to scale the needed level of emergency response, while a more refined spatial analysis may assist first responders in efficiently deploying relief resources where they are needed. Therefore, the estimation of the physical effects of the earthquake on built infrastructure (i.e., rapid damage assessment) provides information that can be leveraged into impact metrics that can be directly used by first responders, such as the number of homeless people following the inability of buildings (i.e., shelter needs) or the number of injured people (i.e., healthcare needs). Rapid damage assessment in this context thus refers to initial estimates of the impact, at any spatial scale (e.g., event scale, municipal scale or district scale), which occurs way before a more detailed inventory of damaged structures. The rapid damage assessment grounds on the evaluation of the peak ground shaking that affected the large epicentral area, that is obtained from the computation of shake maps combining the information derived by strong motion instruments and previously calibrated regional attenuation laws. We will describe here several techniques which are currently used to predict the ground shaking level, the potential damage on building and critical infrastructures and rapid estimates of potential losses in terms of human lives and economical resources.

3.1.2.1. ShakeMap, ShakeCast and PAGER

State-of-the-art and objectives

In the context of Earthquake Rapid Response, the U.S. Geological Survey (USGS) has been developing a set of online services, which may be decomposed as follows:

ShakeMap: shortly after the occurrence of the earthquake, the ShakeMap service produces so-called shake-maps, which are updated ground-motion maps based on the earthquake's characteristics and field measurements or observations.

ShakeCast: this service uses ShakeMap estimates and combines them with pre-defined fragility curves in order to assess the potential impact on critical facilities (e.g., industries, bridges). The objective is to assist facility managers in the application of safety procedures as soon as possible after the earthquake.

PAGER: this service combines ShakeMap estimates with exposure and vulnerability models of built areas in order to deliver a rapid estimate of potential losses induced by the earthquake.

Principles and elements of theory

The most widespread and elaborate shake-map system is the one operated by the USGS, thanks to developments by Wald et al. (1999, 2005). When an earthquake is detected, the magnitude and the location of the hypocenter are estimated. A Ground Motion Model (GMM) is then applied to estimate ground-motion parameters around the hypocenter (each GMM having specific validity criteria such as magnitude range, fault mechanism and dimension, distance to the source, geodynamical context). The observations recorded during the event (i.e., ground-motion measurements and macroseismic intensities when available) are collected and used to update the distribution of the ground-motion field. In the case macroseismic intensities are exploited as observations, a Ground-Motion-Intensity Conversion Equation (GMICE) is used in order to obtain ground-motion estimates. The result consists of a distribution of ground-motion parameters (e.g., Peak Ground Acceleration or Spectral Acceleration at various periods), in terms of mean and standard deviation of a lognormal distribution, across a spatial grid of points.

In the version 4 of ShakeMap, the interpolation scheme is based on the use of the use of the multi-variate normal (MVN) distribution (Stafford, 2012; Vanmarcke, 2010). The vector of ground-motion parameters Y is divided into Y1 (m prediction sites, or grid points) and Y2 (n observations sites). Then, given a set of observations Y2 = y2, a vector of residuals is defined as $\zeta = y2 - \mu Y2$. Thanks to the MVN, it is then possible to express the updated mean and variance of the set of predictions Y1. The initial mean values of Y1 are obtained from a GMM, and the variance-covariance matrix is assembled from the standard-deviations associated with the GMM and from the spatial correlation structure of the ground-motion parameter(s) of interest. Therefore, the results may be directly used as the updated ground-motion distribution for the generation of the shake-map. Worden et al. (2018) also show that this approach enables the consideration of multiple types of ground-motion parameters (e.g., PGA, SA at different periods) simultaneously: thanks to the cross-correlation structure between some ground-motion parameters (esp. spectral responses), it is possible to gain knowledge and constrain shake-maps when only parameters of a given type have been recorded, for instance.

ShakeCast (Lin et al., 2018) uses ShakeMap as input and is based on the HAZUS methodology (FEMA, 2003). Although HAZUS is the default methodology, the user can also introduce specific fragility curves for buildings, bridges, etc. Shake-maps are applied to a list of critical and industrial facilities, for which a probability of damage is estimated through fragility curves.

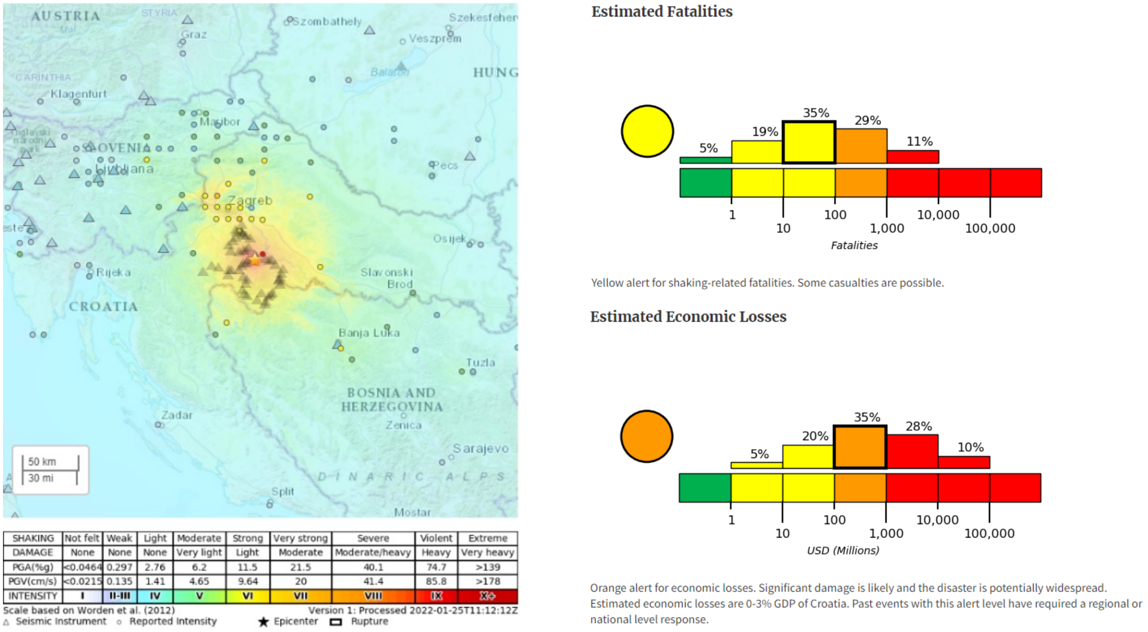


Figure 17 Example of ShakeMap (left) and PAGER (right) outputs for the M 6.2 earthquake near Petrinja, Croatia, on 29 December 2020

The PAGER (Prompt Assessment of Global Earthquakes for Response) system developed by the USGS constitutes a prime example of robust tools used for loss and damage estimation (Wald et al., 2010; Jaiswal et al., 2010). The ShakeMap outputs are combined with vulnerability assessment for loss estimation. Global population databases provide the amount of people exposed to a given macroseismic intensity level, leading to the estimation of potential casualties and economic losses thanks to country-specific vulnerability and loss models (Jaiswal et al., 2010). The approach is empirical in developing regions having experienced an important number of damaging events. In highly developed countries, strong building codes and inventories enable the use of analytical methods, and semi-empirical solutions exist for regions corresponding to a mix of these endmembers. The use of global databases and models makes the PAGER system applicable worldwide, while its automated and fast execution is crucial for a timely sizing of the event and a triggering of appropriate response protocols. Like-country groups are used for the countries without loss data from past events. It does not use regional models as they tend not to be calibrated, particularly for fatalities that requires building inventories, collapse fragilities, occupancy and fatality rates to be approximately correct. Loss estimates are only based on empirical models while other estimates such as the distribution of impacted buildings make use of the other methods.

Since these services are solely focused on earthquake rapid response and not on early warning, they are not concerned by the failure/success rates of the alerts nor the notion of lead time.

Technological requirements

The systems require sensor networks in terms of seismic stations (accelerometers, seismometers) which can detect the earthquake and characterise its parameters: such data is needed as an input to the ShakeMap service. ShakeMap also requires seismic stations (accelerometers, seismometers) and/or testimonies of felt macroseismic intensities (i.e., “Did You Feel It?” online form) in order to constrain the ground-motion field.

The spatial and temporal scale of operation are different depending on method. All systems are delivered within minutes after the occurrence of the earthquake. Then, successive versions are released depending on the integration of additional data. They have a worldwide coverage; however, their accuracy depends on the quality of the data that is input (coverage of the seismic network, map of side effects, exposure model). By default, ShakeMap performs very well for areas such as the United States; yet, in other countries, it is recommended to use independent ShakeMap systems (through the freely available open-source code) that are specific configured to local contexts. The spatial resolution of ShakeMap is configurable (e.g., 1-2 km grid by default), the ShakeCast results are provided at the level of a given facility (point object) and PAGER are given only as a global estimate of losses at the scale of the event is provided.

Operational platforms for alert visualization and dissemination

The processes are fully automated, at least in the early versions of the maps. ShakeMap maps are released on a public web page dedicated to each earthquake event, along with inputs and modelling assumptions. ShakeCast alerts are broadcasted on a web interface and sent by emails and texts to registered end-users in order to be used for prioritizing inspection (green, yellow, orange or red colour tags). For PAGER, loss estimates are released on a public web page dedicated to each earthquake event. Figure 17 shows an example of the web pages of ShaleMap and PAGER. All methods have protocols for alert dissemination and PAGER provides an impact assessment.

Validation

The mathematical soundness of the ShakeMap algorithm has been demonstrated in a study by Engler et al. (2022). Moreover, the continuous computation and storing of ShakeMap and PAGER estimates allows for the aggregation of an extensive database, which may be exploited to review the outcomes and the performance of the services (Marano et al., 2023). Finally, Wald et al. (2002) have detailed the operations, policies and procedures related to USGS rapid response services.

End users

These systems operate in near-real time. ShakeMap and PAGER are made publicly available, and they are also a primary source of information for agencies that trigger international aid and for the reinsurance sector, in order to trigger catastrophe bonds. The ShakeCast service is aimed at critical users, such as business or infrastructure managers.

Pros and cons of the methodology

The ShakeMap method by USGS should be considered as the “gold standard” for the rapid estimation of ground-motion fields since the algorithm has been mathematically demonstrated. The various protocols and procedures that have been put in place throughout the years ensure an optimal continuity of service of the various web platforms. While the ShakeMap system operated by USGS can deliver highly accurate results for the United States, it is still recommended to set up an independent system for other areas, such as European countries, in order to benefit from specific local models and a denser seismic network coverage. Examples of such initiatives are the European ShakeMap service (Cauzzi et al., 2018), the INGV ShakeMap in Italy (Michelini et al., 2020) or the BCSF ShakeMap in France (Schlupp & Bertil, 2019). ShakeMap is freely available as an open-source Python architecture. Moreover, it contains a lot of configurable features, such as the choice of GMMs from the OpenQuake engine (or even combinations of GMMs in a logic tree), choice of the extent and spatial resolution, site amplification, use of point-source or fault-based rupture models, choice of ground-motion parameters, choice of spatial correlation and cross-correlation models for ground-motion parameters, treatment of uncertainties, etc.

A potential issue within the ShakeMap system lies in the characterization of site amplification factors: by default, it uses the Wald & Allen (2007) model based on topographic slope. While this is better than no amplification map at all, and while the influence of amplification factors on the result decreases with increasing ground-motion and or intensity data, there is no guarantee that it provides accurate results for the area of interest. Therefore, regional maps should be used when available, to complement or replace estimated V_{S30} values from topographic data, using the method of Heath et al. (2020) for instance. Recent efforts carried out in the SERA project for a better characterization of site conditions in Europe should be integrated in the upcoming developments.

PAGER aims at providing a picture of the potential impact at the level of the whole earthquake event. This scale is useful for rapidly sizing the disaster and for deciding at which level (e.g., regional, national, international) crisis management operations need to be activated, as well as the amount of aid and resources to dedicate. However, much more detailed information is needed very quickly: usually first responders require a detailed account of the situation at a local level, to establish in which street or building block to operate and to rescue potential casualties.

Also, PAGER is based on predicting damage to common buildings (residential or office types). While ShakeCast can consider infrastructure components or critical facilities, it does account yet for the effect of failed components on the global performance of the infrastructure, which has a great influence on the crisis management operations (e.g., inaccessible roads, power outage, disrupted water supply).

Furthermore, when carried out in PAGER, the estimation of human impacts (fatalities, injuries, homeless people, etc.) is based on empirical methods that are often very simple. These consist in directly applying predefined loss rate to the resident population according to the seismic intensity. Due to the criticality of the estimation of these human losses on decision-making in a crisis management context, further research should be conducted to reduce the associated uncertainty. For instance, by developing methodologies to model population exposure no longer as "static data" as is the case today, but as "dynamic data" considering hourly (accounting for pendulum movements) and seasonal (accounting for tourist populations) changes.

Regarding uncertainty treatment and the communication of probabilistic results, PAGER uses an interesting solution with a rendering format like the Earthquake Impact Scale (Wald et al., 2011), which is as an effort to simplify the challenge of providing very uncertain fatality estimates.

3.1.2.2. SIGE – Information System for Emergency Management in Italy

State-of-the-art and objectives

In the context of earthquake rapid response, an automatic procedure (SIGE - Information System for Emergency Management), activated by the Department of Civil Protection

(DPC), uses the early characteristics of the earthquake event to estimate an expected distribution of structural damage and human casualties.

Principles and elements of theory

The method uses various types of data. INGV provides hazard data, which is used to characterise the earthquake event, i.e., magnitude, epicentre coordinates, hypocentre depth. Exposure data at the level of dwellings is from Italian statistical database ISTAT 2001. Then, using the characteristics of the earthquake communicated by INGV, SIGE-DPC generates a map of macroseismic intensities at the municipal level. However, interestingly, it appears that the shake-map step is bypassed, with no immediate use of measured or observed ground shaking to update intensity maps. The vulnerability model is based on EMS-98 vulnerability, while the distribution of damage grades also follows the EMS-98 damage scale (D0 – D5). Damage assessment is performed through an approach based on Damage Probability Matrices.

Generated outputs are described as follows, at the municipal level (see Figure 18). It provides information on the number of collapsed buildings (D5), the number of non- usable (D3 + D4 +D5). It also provides the consequences in terms of the number of people in collapsed buildings D5 (fatalities estimated 10-30% of this value) and the number of people in non-usable buildings (D3+D4+D5).

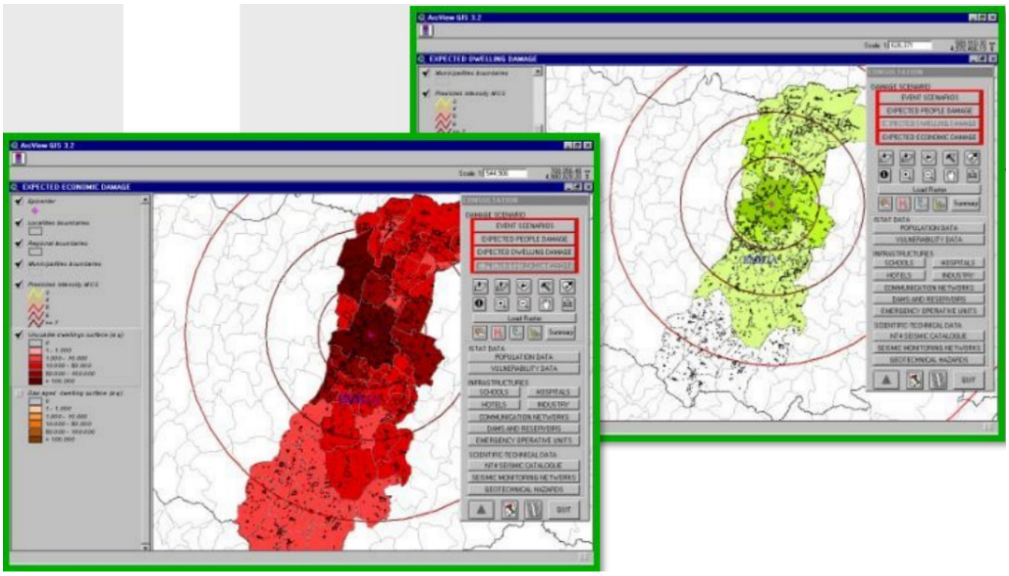


Figure 18 Example of output from the SIGE-DPC system. Source: Dolce (n.d.).

Since this service is solely focused on earthquake rapid response and not on early warning, they are not concerned by the failure/success rates of the alerts nor the notion of lead time.

Technological requirements

The system does not need a sensor network since it directly uses INGV data as input. Results are computed within 20-30 minutes after the event, and the estimation of a damage distribution in built areas and casualties are at the municipal level. All output is processed automatically and alerts are communicated. Protocols of alert and dissemination, and impact assessments exists and is managed by DPC (Italian Civil Protection).

Validation

The review by Dolce (*n.d.*) uses observations from several past earthquakes (e.g., L'Aquila, 2009; Emilia, 2012; Central Italy, 2016-2017) in order to check and validate the results from SIG-DPC. This exercise has allowed for the identification of potential shortcomings and limitations regarding the estimation of damages and casualties.

End users

The system operates in near-real time and is disseminated to local authorities and civil protection mostly.

Pros and cons of the methodology

While the SIGE-DPC tool offers a robust solution, with the consideration of uncertainties and the estimation of damage and casualties at the municipal level, several critical issues have been identified by Dolce (*n.d.*). The hazard modelling considers only a point-source model and you need to choose the most suitable GMMs, given the scenarios. The user also needs to consider and model local amplification effects, which are currently only considered through proxies. Further, they need to include strong-motion records and shake-maps, which are usually available shortly after the earthquake. Finally, they need to include co-seismic effects in the damage scenarios.

For the exposure modelling there is not sufficient information on building inventory, which is currently provided by census, cadastral or satellite images, with no characterisation of structural buildings types and their taxonomy. Exposure is mostly focused on residential buildings, with no consideration of critical facilities, cultural heritage buildings, commercial and industrial buildings, infrastructure, etc. There is no consideration of the evolution of exposure in the case of multiple mainshock sequences.

There is a lack of suitable fragility and vulnerability functions for specific structures. There is no assessment of cumulated damage under repeated shocks. There is a need to generate comparable metrics, by harmonising damage grades, damage ratios, etc., and to properly calibrate of fragility and vulnerability models.

3.1.2.3. SEISAid-Antilles tool: rapid response in French West Indies

State-of-the-art and objectives

In the context of Earthquake Rapid Response, BRGM has developed the *SEISAid-Antilles* system, which, on receipt of an earthquake notification, produces rapid, automatic estimates of potential losses caused by earthquakes affecting the French West Indies. The results of these estimates are automatically fed into a pdf report, the purpose of which is to highlight the potential operational impacts of these assessments in a way that is as easy as possible for practitioners to understand. In doing so, SEISAid-Antilles reports aim to provide very quickly the authorities with relevant information they need to understand the scale of the earthquake and its likely consequences.

Principles and elements of theory

The general principle behind the production of SEISAid-Antilles reports is to estimate the extent of potential losses in less than half an hour, based on a rapid preliminary estimate of the intensity of ground-motions, to provide an anticipated view of both material and human tolls. At the crossroads between the PAGER (Jaiswal et al., 2010) and SIGE tools, the approach adopted for the SEISAid-Antilles system is based on a combination of an intensity map produced with the USGS "Shakemap 4.0" software (Worden et al., 2018) calibrated on field observations (PGA values), and a zoning of buildings that statistically qualifies their vulnerability thanks to fragility curves. This approach enables us to make projections based on a realistic assessment of the seismic intensity, and to refine the calculation of losses on the basis of an explicit consideration of building vulnerability.

As emphasized by Guérin et al (2020), the confidence that users of such rapid response system can place in it requires to be used regularly, not only in the event of a major earthquake, but also for tests, civil protection exercises and planning purposes. Therefore, a test mode has also been developed, enabling SEISAid-Antilles reports to be issued for past earthquakes as well as for fictitious events.

3.1.3. Loss estimations

Rapid earthquake loss estimation methods are crucial for quickly assessing the impact of an earthquake on lives, infrastructure, and the economy. Several methods are proposed here to provide valuable information to emergency responders, government agencies, and policymakers to guide immediate response efforts and prioritize resource allocation. Rapid loss estimation is performed by applying available earthquake scenarios as inferred, for instance, by the ground shaking prediction, to current conditions to estimate casualties, damage, and economic losses. Depending on the available information and its detail at the spatial scale of interest building damage and fragility models allows to predict the vulnerability of different building types to earthquake shaking based on structural characteristics, construction materials, and local ground motion intensity. These models are integrated into loss estimation frameworks to assess the potential damage to buildings and infrastructure systems.

3.1.3.1. Bayesian updating of loss estimates (output from H2020 TURNkey)

State-of-the-art and objectives

In the context of Earthquake Rapid Response, BRGM has been developing a proof-of-concept approach based on Bayesian Networks, in order to update loss estimates with observations gathered in real time from the field. The objective is to constrain uncertainties on loss estimates, at the level of built areas (i.e., damage distribution) and infrastructure systems.

Principles and elements of theory

The proposed loss updating procedure (Figure 19) is articulated around two main types of data.

“Static” data, which includes the conventional models and datasets that are needed to perform conventional risk assessment: knowing the characteristics of the earthquake (magnitude and location), a GMM is applied to estimate the IM distributions at the locations of the exposed elements, accounting for soil amplification factors. Vulnerability models and fragility curves are also used to predict the damage probabilities of exposed elements, given the IM distributions. Finally, in the case of a road network, the knowledge of the graph topology is also needed in order to access system performance measures such as the network connectivity between two points (Argyroudis et al. 2015). All these models put together result in the prior distributions of the variables of interest (i.e., Intensity Measure, Damage State, System Performance).

“Live” data, which represents the observations (strong-motion recordings and damage identification of bridges) that can be entered as evidence in the variables IM and DS. The objective is to constrain the prior estimates by generating posterior distributions of the variables of interest, given the evidence.

All the data is then entered in a Bayesian Network structure, which is solved with OpenBUGS: the sampling inference algorithm generates Monte-Carlo Markov Chains (MCMCs), which contain numerous samples of all variables, given the evidence. These samples are finally used to build empirical posterior distributions, with the effect of improving situational awareness for crisis managers. The loss updating procedure is able to generate a wide range of outcomes, such as damage distributions in built areas, damage probabilities of bridges or the probability that the road network connectivity is lost. The seismic response of bridges may also be updated, given the observations of some damaged bridges, so that updated fragility models may be built and applied to subsequent earthquakes.

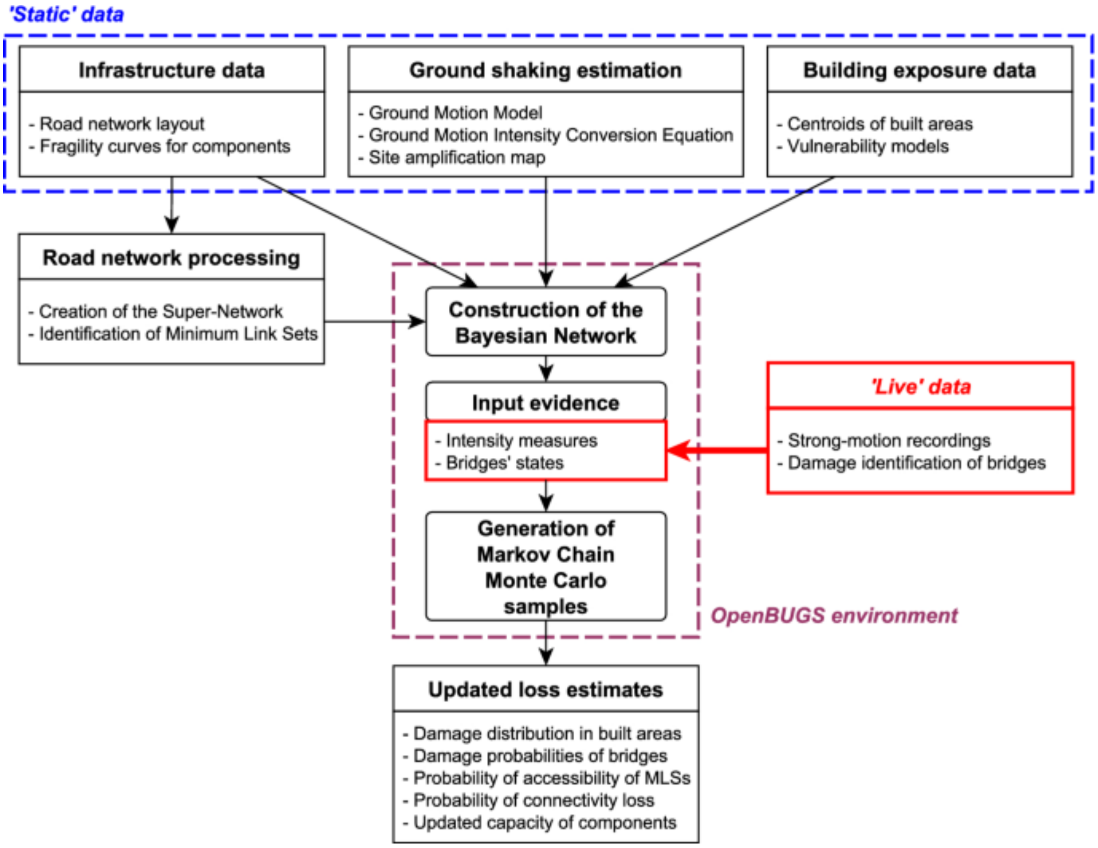


Figure 19 Proof-of-concept of the procedure for the rapid earthquake loss assessment of built areas and infrastructure systems.

Source: Gehl et al. (2022)

Since this algorithm is solely focused on earthquake rapid response and not on early warning, they are not concerned by the failure/success rates of the alerts nor the notion of lead time.

Technological requirements

The system needs sensor networks consisting of seismic stations (accelerometers, seismometers) are required to detect the earthquake and to characterise its parameters as an input to the algorithm. The algorithm also uses three types of observations: measurements from seismic stations (accelerometers, seismometers), testimonies of felt macroseismic intensities (e.g., online surveys) in order to constrain the ground-motion field and reports of damaged infrastructure components (e.g., collapsed road bridge).

Results are computed within 20-30 minutes, depending on the extent of the area and the number of observations to integrate. Estimation of a damage distribution in built areas at the building level. There is need for manual processing and there are no data transmission and alert communication. There are impact assessments for built areas and infrastructures.

Validation

The algorithm has been demonstrated by Gehl et al. (2022) on a virtual seismic scenario on the built areas and road network near Bagnères-de-Luchon (Pyrénées mountain range, France). However, the approach has not yet been validated on an actual case.

End users

The algorithm is designed to operate in near-real time; however, it is currently only available as a proof-of-concept version for offline use. If developed further, this tool should be destined to local authorities and civil protection mostly, due to the accurate spatial resolution at which it operates and to the communication of uncertainties (i.e., not suitable for a large public).

Pros and cons of the methodology

The proposed Bayesian approach contains very innovative features. It is a probabilistic framework that accounts for the propagation of uncertainties, from hazard to losses. It contains modelling of the loss of performance infrastructure systems and of the interactions between components, in order to have a more complete vision of the crisis (i.e., lack of accessibility of various areas). It also integrates multiple sources of observations, such as ground-motion measurements from seismic stations, macroseismic intensities or damage observations, in order to constrain projected loss estimates. However, this method is currently only at the stage of a proof-of-concept, and the next immediate step would be to validate it by replaying the scenario of a past damaging earthquake and by adding all sources of observations as they were made available at that time. Then, building a robust and operational version would be another required step, in order to move up the TRL of this approach.

3.1.3.2. ELER System – Earthquake Loss Estimation Routine for Turkey

State-of-the-art and objectives

In the context of Earthquake Rapid Response, KOERI, Imperial College, NORSAR, and ETH-Zurich have developed a methodology for rapid loss assessment within the NERIES EU project (Hancilar et al., 2010): the ELER (Earthquake Loss Estimation Routine) methodology. This is a capacity spectrum-based method that performs loss estimation (building damage, casualties, economic loss), and that uses building inventories (type, height and year) for the vulnerability assessment. At a high-resolution level, the damage on buildings and associated uncertainties are evaluated using spectral displacement-based analytical vulnerability relationships. This ELER's routine is today mainly used by the Istanbul rapid response system (Zülfikar et al., 2017), with a nationwide use in Turkey as well.

Principles and elements of theory

The ELER methodology and software is operational in Turkey both at the country scale, and at the city scale (for Istanbul only). At the country scale, immediately after an earthquake in and around Turkey, intensity shakemaps are automatically generated by ELER and published by KOERI-RETMC Then, as recorded ground-motion data become available, bias adjusted shake maps and intensity-based building damage estimation maps are manually reproduced.

In the case of Istanbul, it is a separate system that does not use the KOERI-RETMC shake maps. Instead, ELER produces PGA, PGV, Sa and intensity shake maps, incorporating recorded strong ground-motion data by IEEWRRS. The Vs30 based on local soil information is also considered. Then, the calculations of damage and loss are performed on a grid using, in addition to the shake maps, exposure and vulnerability data. The grid-based building inventory was first compiled by using the year 2000 Turkish Statistical Institute (TUIK) Building Census (including information on the construction year, number of floors, and building construction type and the demographic data). In a second step of the project, a district-based building inventory of Istanbul was performed to complete the TUIK statistics and the final inventory was finalized into 0.005° grids by using 2008 building line geometries of 1/1000-scaled existing maps. The building damage is evaluated using the ELER methodology, and the loss estimation with the HAZUS-MH methodology (FEMA, 2003).

Technological requirements

No sensor network exists for nationwide system, as the shake maps calculated by KOERI/RETMC are used as input data. However, it exists for the Istanbul system. Both systems are fully automatic with data transmission and alert communication through the 3G GSM network.

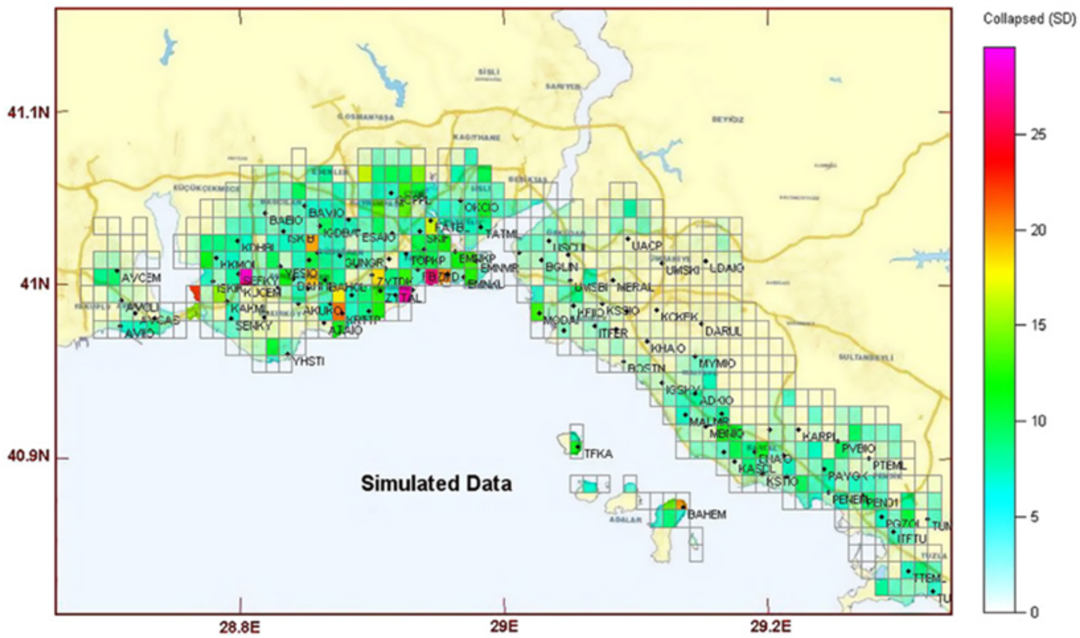


Figure 20 Example of a rapid damage assessment map in Istanbul after a magnitude 4.3 earthquake that occurred on March 12, 2008.

Source: Erdik et al., 2011

Operational platforms for alert visualization and dissemination

There are no known platforms for alert visualization and issuing, also no protocols for alert dissemination. There is an impact assessment which provide damage to residential built areas and impact to daytime/night-time resident population. The resource is managed by Kandilli Observatory and the Earthquake Research Institute - KOERI).

Validation

The implementation of the rapid response system for Istanbul began in 2001, with a major update in 2012: then, the current system has 10 years of experience. However, we are not aware of any validation of the system on real earthquakes.

End users

Today, the system is used both online to produce damage estimates for Turkey, and - with greater precision - for the metropolis of Istanbul but can also be used offline to create scenarios (Figure 20). The prime end users are the Istanbul Governorate, Istanbul Municipality, First Army Headquarters.

Pros and cons of the methodology

In terms of rapid earthquake detection, Istanbul's rapid response system is based on a very dense monitoring network of around 100 stations. The system is able to consider extended faults by assigning the earthquake to the nearest known fault segment. If no association is possible, a point-source is considered instead. Consideration of geological site effects integrates microzoning data and local geological knowledge (Zülfikar et al., 2017). However, although indicated as being "similar to the USGS's ShakeMap" (Zülfikar et al., 2017), the intensity map calculation process remains poorly documented.

Exposure is mostly focused on residential buildings, with no consideration of critical facilities, cultural heritage buildings, commercial and industrial buildings, infrastructure, etc. There is no consideration of the evolution of exposure in the case of multiple mainshock sequences. The vulnerability modelling use of fragility or vulnerability functions from the HAZUS methodology (FEMA, 2003) without adaptation to local building conditions in Turkey. There is a need to consider cumulated damage under repeated shocks.

3.1.3.3. QLARM - Quake Loss Assessment, Response and Mitigation

State-of-the-art and objectives

QLARM estimates the numbers of fatalities, the number of injured and the mean damage degree in settlements strongly affected within 22 minutes, median, after the first source parameters of significant earthquakes are distributed by the Geoforschungszentrum (GFZ) at any hour of the day worldwide. The structure of the computer code QLARM is described by Trendafiloski et al. (2011) and a report on the first 10 years of its operation is contained in Wyss (2014). Only significant earthquakes in populated areas are considered. The alerts distributed manually number more than 1380 since October 2002. QLARM is the only source that has declared red alerts within near-real-time for the recent earthquake catastrophes in Turkey (M7.9, 6 February 2023), Morocco (M6,9, 8 September 2023) and Afghanistan (M6.5, 19 November 2023). The alerts are distributed by email to anyone who wishes to receive them, and on the website X (ex-Twitter).

Principles and elements of theory

The input for loss calculations by QLARM is hypocenter and magnitude (M). It is provided by GFZ and the US Geological Survey for earthquakes worldwide. The exact depth is poorly known by the first tele seismic calculations. The strike of the rupture and its end points are not known at first. The lack of this information is currently the largest source of uncertainties in QLARM alerts because point sources have to be used, instead of more realistic line sources. Once the azimuth and length of the rupture is known, QLARM can calculate losses, based on intensities (accelerations) using the shortest distance to a line source modelling the rupture.

Several attenuation functions are coded in QLARM, but for most locations in the world, specific attenuation properties are not known. Therefore, an average attenuation function is used for first calculations of ground motions (Shebalin, 1968). The objects at risk in QLARM are settlements for which the estimated number of population and the distribution of buildings into resistance classes are listed. In developed countries, the populations and names for all settlements are known. In most earthquake-rich countries the population distribution must be constructed. Commonly, the population numbers for the largest settlements (cities) and that of the entire country are known from national web sites and that of the CIA, respectively. For small settlements only the names are listed on the website "geonames". Thus, we assume that the population in each of these small settlements equals to a constant that leads to the population number given by the CIA for the whole country, when the population in all known settlement is summed.

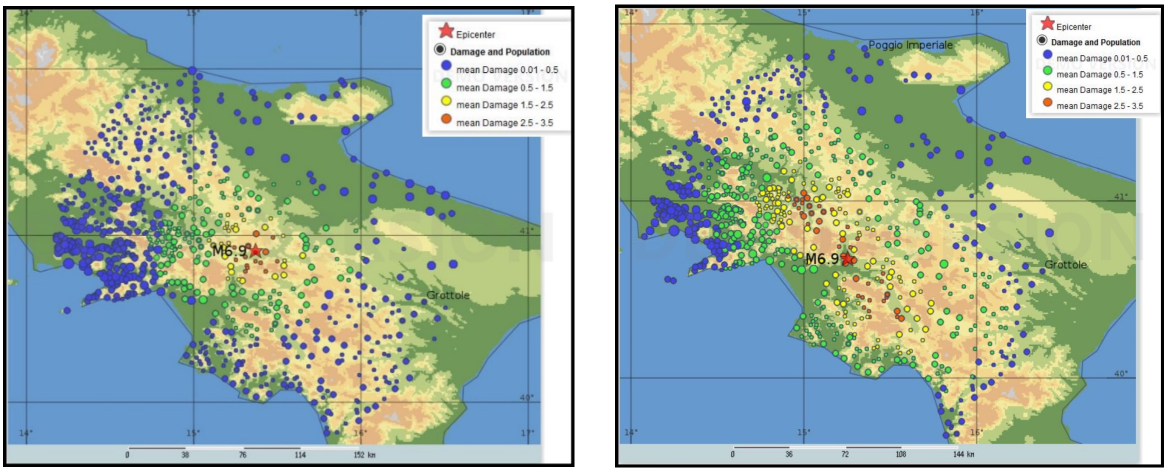


Figure 21 Maps of the mean damage due to the Irpinia M6.9, 1980, earthquake.

Left modelled as a point source, right as a line source. The star marks the epicentre, each dot denotes a settlement with size proportional to the population. From Wyss and Rosset (2018). Based on the after-the-fact analysis of the fatalities due to the Irpinia M6.9 and the real-time estimate of the M6.3 L'Aquila earthquake, it is established that QLARM correctly estimates fatalities for earthquakes in Italy.

The built environment is modelled, using the EMS98 classification of buildings into 5 classes with separate resistance to shaking from the weakest class A to the most resistant engineered class F (Trendafiloski et al., 2011). For some countries in the developed world the distribution of buildings in resistant classes are known. In countries with the most fatal earthquakes, they are not known. Therefore, QLARM contains a simplified model in which the built environment is assumed to be the same in all settlements belonging to one of three size classes: In villages weak buildings dominate, in towns their properties are intermediate, and cities contain strong engineered buildings. The occupancy rate of the different buildings is derived from various information contained in national and other web sites. The occupancy rate is modelled as a function of the hours of the day, with most people inside buildings at night and least during daytime.

Local amplification of strong seismic motions is modelled by district for a number of large cities. However, a general amplification model based on Vs30 is not yet implemented. Calibration of QLARM fatality estimates have been performed for several countries (e.g., China, Italy, India, Pakistan, Mexico, Iran, Colombia) by approximately matching reported macroseismic maps and fatality numbers with QLARM calculations for historic earthquakes. Successful matches have allowed constructions of earthquake loss scenarios for likely future earthquakes in these countries.

Validation

The M6.9 Irpinia earthquake, 23 November 1980, provided an ideal test case for verifying the applicability of QLARM in Italy. Wyss and Rosset (2020) modelled the effects on buildings by this earthquake in a point source and a line source configuration (Figure 21). The number of fatalities estimated by QLARM, based on a point source, is 300 to 1,840, slightly smaller than the reported fatalities of 2,483. The QLARM estimate based on a line source 780 to 5,840 correctly brackets the observation. Details on this analysis and on the real-time estimate of fatalities in the M6.3 L'Aquila earthquake of 2009 are given by Wyss and Rosset (2020).

End users

Real-time performances of QLARM in the target countries for earthquakes with fatalities or injured reported later number 17. A list including report delay and fatality estimates is available.

How will GOBEYOND take this to the next level?

Speeding up the QLARM estimates can be achieved firstly, by automatically issuing it to 7 minutes, worldwide. If local seismograph networks can deliver source parameters within 1 minute of earthquake occurrences, then QLARM can issue preliminary earthquake loss estimates within 2 minutes. Based on the current 22 minutes delay of manual world-wide QLARM loss estimates, one can expect that for the **GOBEYOND** target areas reviewed loss estimate will become available 24 minutes after an earthquake occurrence.

3.2. Volcanoes

3.2.1. Volcanic earthquakes and ash fall evaluation

Volcanic eruption early warning and rapid response systems aim to provide timely alerts and mobilize response efforts to minimize casualties, property damage, and disruptions to infrastructure related to the eruption occurrence and related effects such as seismic activity and ash fall. As compared to the earthquake hazard, "early warning" is here meant to issue an alert based on precursory phenomena (geochemical indicators, seismicity, ground deformation, among others) occurring before the eruption occurrence. A key role is played by the volcano monitoring system consisting of seismic stations, GPS instruments, gas sensors, and satellite imagery that continuously monitor volcanic activity. Changes in seismicity, ground deformation, gas emissions, and thermal anomalies can indicate volcanic unrest and impending eruptions. In **GOBEYOND** we primarily focus on the volcano related seismic hazard and ash fall forecasting models that predict the dispersion and trajectory of volcanic ash clouds following an eruption.

3.2.1.1. State-of-the-art and objectives

An efficient management of the effects due to volcanic eruptions on urban areas need their damage preliminary assessment on the territory. Since 2006, PLINIVS is a National Competence Centre on Volcanic Risk for the Italian Civil Protection. In this framework, with the aim to support planning and management of emergency, PLINIVS developed a probabilistic simulation tool, called EASE (Earthquake AShfall Evaluation) able to furnish risk analyses consequent two main phenomena (precursor earthquakes and ash fall) induced by possible explosive volcanic eruptions of the Campanian volcanoes (Vesuvius, Campi Flegrei and Ischia). EASE tool can develop damage automatic simulations due to seismic events and ash fall, on the base of hazard data furnished by INGV (National Institute of Geophysics and Volcanology).

3.2.1.2. Principles and elements of theory

For each minimum reference unit of analysis (250 x 250 m square cell), the impact is assessed as the number of buildings with local or total collapse and the number of casualties (dead, injuries and homeless) among the building's occupants. The methodology at the base of the model implemented in the EASE tool is an impact scenario analysis, which is different from a risk analysis.

The "risk" is the probability to reach a predetermined level of damage on given element exposed (people, buildings, infrastructures, economy, etc.) caused by volcanic events occurring in a given period of time and in a certain geographical area. The risk should be considered as a cumulative assessment, related to the potential total damage generated by all volcanic events that can occur in given area in a predetermined time interval.

The "scenario", instead, represents the probabilistic distribution of the damage, in a given geographical area, caused by a single volcanic event of intensity "I" (chosen as scenario of reference), with assigned probability of occurrence (reference scenario). In both analyses, three aleatory variables (hazard, exposure, and vulnerability) must be considered (Unesco, 1972; Fournier d'Albe, 1979).

In case of earthquakes, the measure of the event (hazard scenario), in terms of epicentre position, depth and magnitude, is furnished by the monitoring system recordings of INGV, accessed by PLINIVS through standard FDSN Web Services (International Federation of Digital Seismograph Networks).

In case of ash fall, the phenomena dimension, in terms of ashes loading on the ground, is furnished by INGV, through daily simulations for the Campanian volcanoes, according to different possible eruptive scales (e.g., small, medium, and large) and depending on the probable direction of the stratospheric winds.

The "exposure" and "vulnerability" models adopted in the EASE tool are developed by PLINIVS (Zuccaro and De Gregorio, 2019), on the base of data collection activities on built environment and population, at national and regional scale, that allowed building up a comprehensive GIS database, that includes population data, classification of different building typologies (detailed at the level of technical elements: structure, wall, roof, opening, etc.) and features of transport networks.

3.2.1.3. Technological requirements

The system does not directly use sensors or sensors networks. The spatial scale of operation is limited to Campania Region for earthquakes and ashfall impact evaluations.

For EARTHQUAKE simulations, the process is founded on automatic acquisition of seismic event data. As the events are asynchronous and unpredictable, the procedure is executed at regular and configurable time intervals (in the order of minutes), and the seismic data published by the INGV FDSN Web Services (International Federation of Digital Seismograph Networks) acquired as an increment over to the last events already downloaded. Seismic hazard data are stored in the event database Event Archive EQ, and if the recorded event meets the parameters of geographic location and recorded magnitude configured in the application, the seismic impact simulation and the results stored and made available through the EQ Events Impact menu item. The model elaboration time and results storage are in the order of minutes.

For ASH FALL simulations, the process is founded on automatic acquisition process of volcanic hazard scenario. The procedure is executed with an asynchronous timed event scheduled with the times of availability of ashfall scenarios produced by INGV (from once a day to every 8 hours according to the attention level for the volcanic event); the hazard data are stored in the ASH Event Archive event database, and produced ashfall impact scenarios are stored in Impact Events ASH archive. The model elaboration time and result storage are in the order of minutes. The system does not use an alert communication system. The produced results are accessible directly through the user interface of the web application, and through OGC services (WMS/WFS) so that they can be integrated in other web map applications and/or GIS clients for visualization and further analysis.

3.2.1.4. Operational platforms for alert visualization and dissemination

EASE tool is available at the Volcanic Service of the Italian National Civil Protection Department and at the Civil Protection of the Municipality of Pozzuoli, to support the planning and management of the volcanic emergency (Figure 22). To date, there are no protocols for alert dissemination.

For any seismic events recording by INGV, the tool furnishes the real time estimation of expected impact of on the territory, in terms of number of collapsed and uninhabitable buildings and dead, injured and homeless, in each 250x250m cell. This information is useful to manage the early phases of the emergency and coordinate Search and Rescue activities.

For any simulations on ash fall distributions (1simulation/day in peace time, 3 simulations/day in alarm phase), in function of the probability of stratospheric winds direction and the eruptions scale (Vesuvius: medium; Campi Flegrei: small, medium, large), EASE develop the impact assessment on the territory, in terms of number of collapsed roofs, unsafe buildings and homeless, in each 250x250m cell.

3.2.1.5. End users

EASE tool is used for a “near real-time” use. The impact maps are automatically developed, in about 2-5 minutes once the hazard data is received from INGV. The EASE tool is available at the Volcanic Service of the Italian National Civil Protection Department and at the Civil Protection of the Municipality of Pozzuoli, to support the planning and management of the volcanic emergency.

3.2.1.6. How will GOBEYOND take this to the next level?

EASE tool was created to support planning and management of volcanic emergencies and not for early warning communication. EASE could be integrated into the **GOBEYOND** platform, and it could also be designed for an early warning system, e.g., to disseminate information on roads interrupted by precursor earthquakes (unrest phase) or on the distribution of areas potentially affected by roof collapse due to ash fall, depending on the direction of stratospheric winds (alarm phase).

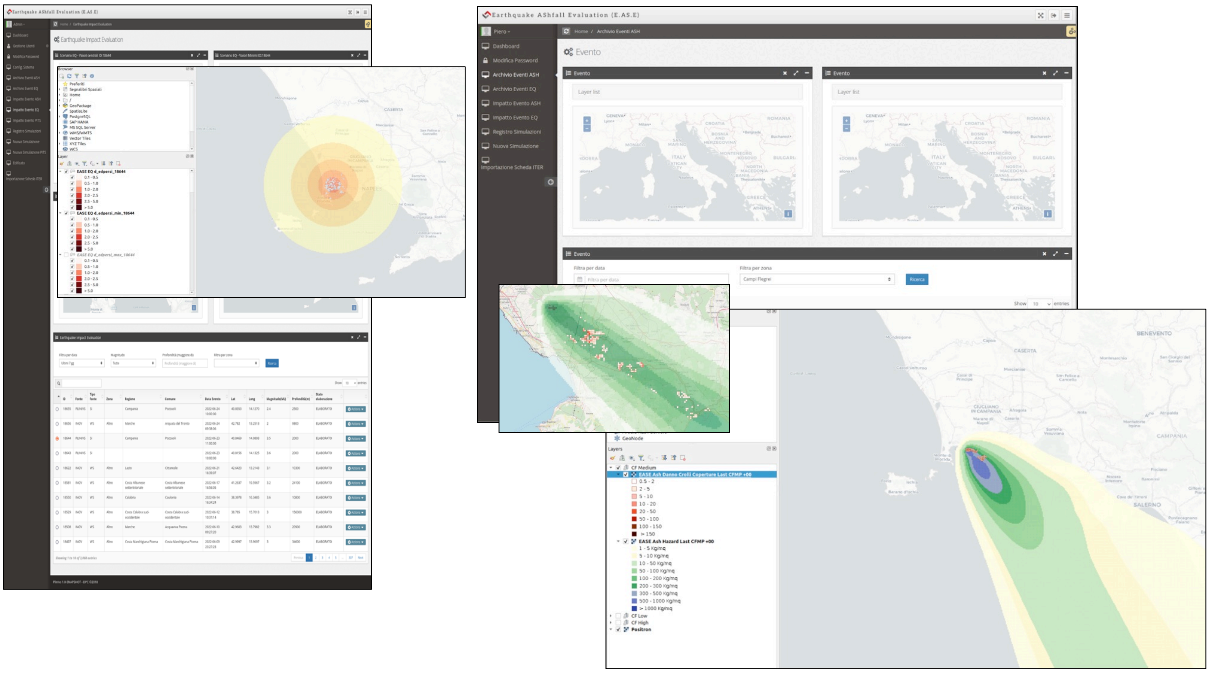


Figure 22. EASE tool: Impact scenario analyses consequent earthquakes and ash fall at the volcanoes of Campania Region (PLINIVS-UNINA).

3.2.2. Volcanic ash early warning systems

3.2.2.1. State-of-the-art and objectives

The Satellite-Based Monitoring and Atmospheric Modelling methodology utilized by key international Organizations such as NASA, ESA, NOAA, National Meteorological Agencies and Volcanic Ash Advisory Centers (VAACs), integrates satellite-derived information for monitoring and advisory services. Specifically, nine VAACs are tasked with monitoring the movement of volcanic ash within their assigned airspace (Figure 23; ICAO 2007) to inform the aviation community about volcanic hazards. This collaboration improves the accuracy of Early Warnings for aviation safety. Leveraging advanced Earth-Observing satellites such as MODIS, VIIRS, and Sentinel, the methodology achieves real-time monitoring and tracking of volcanic ash clouds. Advanced atmospheric dispersion models and automated algorithms enhance prediction accuracy, placing the methodology at the forefront of technology for comprehensive volcanic ash event understanding and forecasting.

The primary objectives of this methodology are multi-faceted:

- Enhance Forecast Accuracy
- Global Coverage and Collaboration
- Automate Data Processing
- Improve Atmospheric Dispersion Models
- Enhance Communication Protocols
- Research and Development

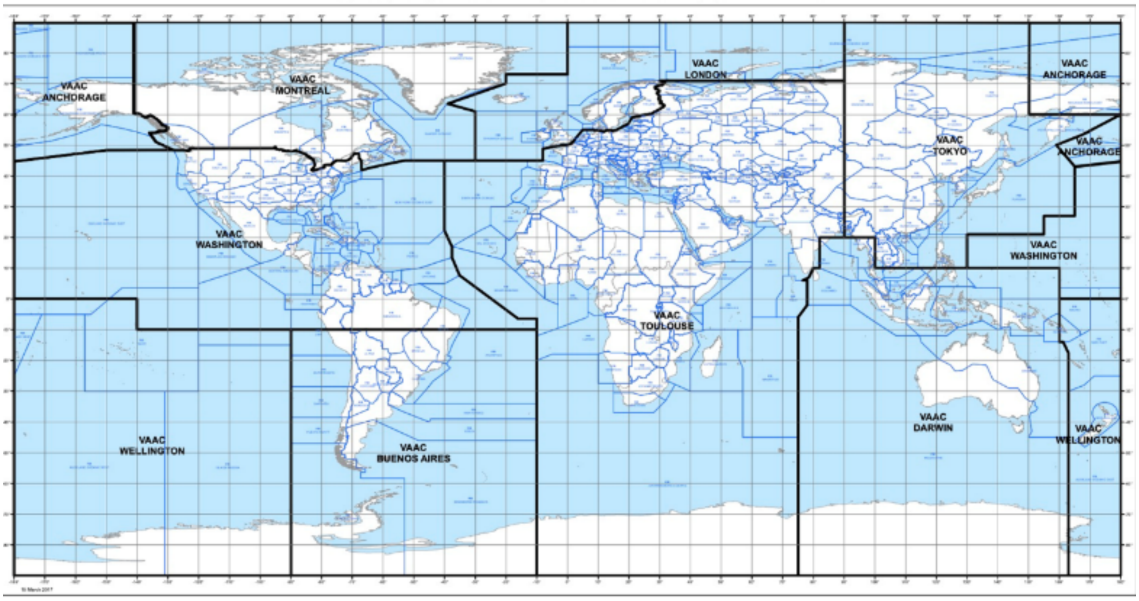


Figure 23. Current status of ICAO Volcanic Ash Advisory Centres (VAACs).

3.2.2.2. Principles and elements of theory

The methodology employs a synergy of satellite data analysis and atmospheric dispersion modelling to derive the output. This comprehensive approach facilitates the prediction of volcanic ash cloud transport and the identification of concentration at various altitudes through the utilization of automated algorithms. The process involves leveraging satellite imagery for the detection and tracking of ash clouds, coupled with a thorough analysis of optical and thermal characteristics of ash plumes. Additionally, specialized early warning systems (EWSs) are integrated and offer short-term forecasts of volcanic ash clouds based on comprehensive satellite and source information (Stohl, A. et al, 2011). The accuracy of these forecasts, particularly concerning the long-range transport of volcanic particles, hinges on assumptions related to the injection height at the source, often modelled as a straightforward function of the mass eruption rate in many EWSs (Webley, P. & Mastin, L., 2009).

The methodology's success based on accurate forecasting of ash cloud movement and concentration, gauged through precise predictions and timely adaptability to real-world events. This evaluation considers uncertainties from eruption source parameters and meteorological factors. Alignment of issued alerts with observed ash cloud behaviour, speed of response, and appropriateness of recommended actions are key factors assessed. Failure is determined by analysing deviations and the methodology's ability to provide actionable insights for effective decision-making in unforeseen challenges. Uncertainties in deterministic transport and dispersion models are associated with the eruption source parameters (e.g., total mass, plume height), model parametrizations, and driving meteorology (Dacre, H. F. & Harvey, N. J., 2018; Plu, M. et al., 2021; Amiridis, V. et al, 2023).

National meteorological agencies and VAACs, plays a crucial role in volcanic ash monitoring, integrate satellite data for real-time updates on ash cloud movement. Collaborating closely with aviation authorities, VAACs issue timely alerts, enhancing lead time for preparation. The methodology focus on advanced remote sensing and data analytics reinforces its commitment to providing accurate information for aviation safety, contributing to an effective early warning system with extended lead time.

3.2.2.3. Technological requirements

This method relies on Earth-observing satellites like MODIS, VIIRS, and Sentinel satellites, ensuring high repetition cycle observations for lava flows and ash clouds (See Table 2). However, there's an observational gap for high-resolution TIR/MIR multispectral sensors crucial for locate thermal anomalies and small gas emissions during pre-eruptive phase of volcanoes. Future missions, like ESA/EUMETSAT – SENTINELS, are expected to address these gaps (Prata, A. J. & Prata, A. T., 2012).

Table 2 Sensors, resolutions, revisit times and bands available from current and some proposed satellite instruments useful for early warning/precursors

Satellite - Sensor	TIR Spatial Resolution	Day/Night	Revisiting Time	# TIR bands	SWIR bands
MSG - SEVIRI	3 to 5 km	D, N	Geostationary (15 min)	5	1
NOAA – AVHRR	1.1 km	D, N	12 hr	2	1
METOP – AVHRR-3	1.1 km	D, N	Daily	2	1
TERRA, AQUA – MODIS	1.1 km	D, N	Daily	10	4
ERS1 – ATSR ERS2 – ATSR-2	1 km	D, N	3 to 5 days	2	1
ENVISAT – AATSR	1 km	D, N	3 to 5 days	2	1
LANDSAT – TM / ETM	120 m 60 m	D [N]	16 days	1	2
TERRA – ASTER	90 m	D	16 days	5	6
SENTINEL-2 MSI	30 – 60 m	D [N]	5 days (2 satellites)	0	3
SENTINEL-3 SLST	500 – 1 km	D, N	5 days (2 satellites)	2	3

This method employs automated procedures for volcanic ash dispersion forecasting, utilizing daily meteorological data and running tephra dispersal models. It issues advisories and charts every 6 hours during eruptions, offering guidance up to 18 hours ahead. Annotated satellite images are provided every three hours. To meet International Airways Volcano Watch program obligations, meteorologists monitor inactive volcanoes for re-suspended ash threats. VAAC Forecasters use an 'intervention tool' for adjustments based on observations before issuing graphical advisories.

After the event of an eruption, Volcanic observatories issue the Volcano Observatory Notice to Aviation (VONA). Following the guidelines of the Handbook on the International Airways Volcano Watch (IAVW), VONA messages utilize a color-coded alert system to convey information about the presence and quantity of volcanic ash in the atmosphere. These messages are transferred to various entities, including the Meteorological Watch Office (MWO), the Volcanic Ash Advisory Centres (VAAC), the Area Control Centre/Flight Information Centre, and the National Network Manager. After that, are disseminated to national aviation and government authorities.

3.2.2.4. Operational platforms for alert visualization and dissemination

The Volcanic Ash Advisories (VAA) and Volcanic Ash Graphics (VAG) are the official VAAC products used to alert of volcanic activity across the impacted areas and depict how the activity will evolve over a given time range. This information proves valuable to core partners that include Domestic and International Airlines, Air Traffic Control and Operational groups (ARTCCs and ATCs). The protocols for Alert dissemination are the established systematic procedures in collaboration with aviation authorities to issue alerts and advisories. Integrates satellite-derived information into monitoring and advisory services.

The impact assessment focuses on aviation safety, assessing potential risks to air traffic. It supports decision-making by aviation authorities based on forecasts. The management agencies Involves regional VAACs in collaboration with national meteorological agencies, Civil Protection Agencies, and aviation authorities. This collaboration enhances the accuracy of early warnings for aviation safety. The management agencies can vary based on the region and the organizational structure in place for handling volcanic ash events.

3.2.2.5. End users

This methodology performs well both in real-time, during live events, and offline, in a retrospective analysis of its predictions in comparison to actual outcomes. This dual assessment provides a more holistic understanding of the methodology's strengths and weaknesses in different operational contexts. Primary end-users include aviation authorities, airlines, and meteorological agencies. Academic institutions may also benefit from the data for research.

3.2.2.6. Pros and cons of the methodology

The advantages of the methodology are many. The methodology excels in providing highly precise forecasts for volcanic ash cloud movement and concentration, contributing to enhanced aviation safety. Real-time monitoring capabilities, facilitated by advanced satellite technology, enable timely responses to volcanic events, minimizing potential risks. The methodology fosters global collaborations, leveraging data and expertise from international organizations, leading to a comprehensive and well-informed approach. Automation in data processing enhances efficiency, ensuring rapid analysis of satellite-derived information and swift issuance of alerts. Utilization of sophisticated numerical models for atmospheric dispersion enhances the accuracy of predictions, contributing to improved decision-making.

The limitations are that the deterministic transport and dispersion models may have uncertainties, particularly associated with eruption source parameters and meteorological factors, affecting the accuracy of forecasts. The methodology also heavily relies on satellite technology, and disruptions or limitations in satellite coverage can impact the effectiveness of monitoring and forecasting. Extending lead times for forecasts may face challenges, potentially hindering the ability to provide longer preparation periods for authorities and stakeholders.

The major sources of uncertainties in deterministic transport and dispersion models pose challenges to scientific progress. Improving the modelling of eruption source parameters and refining parametrizations remains a priority. For more accurate volcanic ash transport simulations, emission mass rates can be calculated through inversion techniques and initiate the transport models.

3.2.2.7. How will GOBEYOND take this to the next level?

Invest in advanced research and development to address modelling uncertainties and technological limitations. To remain at the forefront of advancements in volcanic ash monitoring and forecasting, it is crucial to embrace emerging technologies. For more accurate simulations, a synergy of satellite, ground-based and model data for monitoring the transport pathways and quantifying the number of volcanic emissions, can be used. Further improvements are achieved by incorporating emission mass rates, calculated through inversion techniques, to initiate the transport models, deepens the understanding of volcanic ash dynamics. Foster even stronger collaborations and data-sharing initiatives. Engage with a wider network of international agencies to enhance the methodology's data collection and accuracy.

3.2.3. Volcanic ash rapid response

3.2.3.1. State-of-the-art and objectives

The Ground-based Lidar methodology, exemplified by the Icelandic Meteorological Office (IMO), represents a cutting-edge approach to volcanic monitoring and forecasting. Leveraging a combination of remote sensing technologies and advanced data analytics, the IMO utilizes a multi-sensor integration system to comprehensively monitor volcanic activity. The implementation of ground-based lidar systems for real-time monitoring of volcanic ash particles adds a critical dimension to the observational capabilities. The methodology integrates real-time data from various sensors into a centralized system, enabling accurate simulations and risk assessments. The IMO's Decision Support System, automated alerting system, and effective communication strategies contribute to the state-of-the-art in volcanic hazard management.

The main objectives which aim to enhance the methodology's effectiveness in monitoring and forecasting volcanic ash activity are:

- Multi-Sensor Integration and Data Fusion
- Lidar for Real-time Monitoring
- Implementation Details
- Risk Assessment
- Decision Support System
- Automated Alerting System
- Public Communication and Education

3.2.3.2. Principles and elements of theory

The IMO combines remote sensing and data analytics to calculate the output. They employ satellite data for thermal and optical imagery, utilizing automated algorithms and machine learning models to analyse changes indicative of potential eruptions. Failure or success of the IMO is calculated using probabilities and is determined by deviations between forecasted and observed volcanic conditions. The methodology aims to provide early detection by monitoring changes in volcanic conditions in real-time.

3.2.3.3. Technological requirements

The IMO operates a network of ground-based sensors, including spectrometers, seismometers, gas analysers, thermal cameras, and ground-based lidar systems (Figure 24). The methodology covers comprehensive monitoring of volcanic activity in Iceland using a combination of ground-based and satellite-based systems. Real-time monitoring integrates data from various sensors into a centralized system. Advanced numerical models are used for ash dispersion simulation based on real-time data (Figure 24). An automated alerting system, triggers warnings based on predefined thresholds. Communication to the public is facilitated through an early warning system.

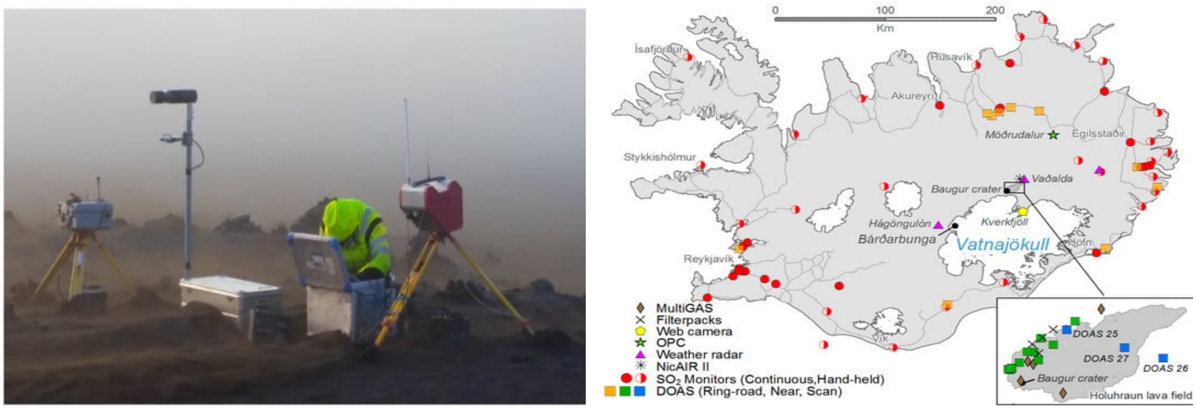


Figure 24 Volcanic monitoring instruments.

A) ScanDOAS instrument (Differential Optical Absorption Spectrometry -DOAS), at Þorvaldshraun Volcano, Iceland. B) Map of Iceland showing the locations of the ground-based volcanic cloud monitoring instruments. An inset of the area around the eruption site is enlarged. The DOAS instruments are identified by number. For more details see Pfeffer et al., 2018 study

3.2.3.4. Operational platforms for alert visualization and dissemination

IMO employs a Decision Support System with a real-time monitoring dashboard for authorities to assess the situation and issue timely alerts. As part of the procedures, the aviation colour code is operated to inform the aviation sector about potential dangers associated with volcanic activity. After an eruption VONA alerts are sent out via email to a list of addresses, the Aviation Colour Code (ACC) is automatically changed on the online map on IMO's website as well as in the Catalogue of Icelandic Volcanoes, and eventually the VONA is made available on the web.

The natural hazard specialist (NHS) monitors the real time data coming in and integrates, in a multidisciplinary way, the information to assess any impending hazards. Contingency plans exist to guarantee fast communication with key stakeholders including the local Civil Protection, the London- VAAC and ISAVIA (the Icelandic navigation service provider). The methodology incorporates an automated alerting system that disseminates warnings based on predefined thresholds for ash concentration, wind patterns, and other critical factors. The IMO uses modelling to assess the risk of volcanic activity and evaluates potential impacts on air quality and public health. The IMO is the primary agency utilizing this methodology for monitoring and forecasting volcanic activity in Iceland.

3.2.3.5. End users

The Ground-based Lidar methodology is designed for real-time operational use through automated alerting and decision support systems. Additionally, the methodology involves offline use of advanced numerical models to simulate ash dispersion based on historical and real-time data. This offline modelling allows for dynamic and accurate predictions, contributing to hazard assessment and risk evaluation. The end-users include academic researchers, local authorities responsible for public safety, civil protection agencies, and the general public.

3.2.3.6. Pros and cons of the methodology

The advantages of the system are an early detection, real-time monitoring, comprehensive risk assessment. Limitations are potential false positives and dependency on accurate data input. The major challenges include refining modelling uncertainties, improving eruption source parameter modelling, and addressing technological limitations in data collection and processing.

3.2.3.7. How will GOBEYOND take this to the next level?

GOBEYOND aims to invest in advanced research and development to enhance modelling accuracy, embrace emerging technologies for more precise simulations, and foster stronger collaborations for improved data collection and accuracy. By incorporating better initial eruption conditions from a synergy of satellite and ground-based observations and higher resolution meteorological data, the project seeks to elevate the quality of simulation results. This enhancement is particularly critical when utilizing simulation outcomes for aviation safety purposes.

3.3. Tsunamis

Tsunamis can be large scale phenomena that can propagate across oceans. They can impact areas in a wide extension. Tsunami warning systems are then organized at ocean scale, in an intergovernmental context. The coordination of the global tsunami warning and mitigation system is assured by the Intergovernmental Oceanographic Commission of the UNESCO (IOC): Four regional systems are coordinated by the Intergovernmental Coordination Groups (ICG, Figure 25). Historically, tsunami warning systems have been built or improved in response to catastrophic events. The Pacific Tsunami Warning System (IGC/PTWS) operates since 1965 after the M9.5 1960 Chilean earthquake, it is the first ocean wide tsunami warning system, whereas following the M9.1 2004 Sumatra tsunami, tsunami warning systems appeared for the Caribbean and adjacent regions (IGC/CARIBE-EWS), Indian Ocean (ICGIOTWMS), and the North-Eastern Atlantic, the Mediterranean and connected seas (ICG/NEAMTWS). A Tsunami Service Provider (TSP) provides information about events and communicate to Tsunami Focal Warning Points (TWFP) in each country, and the National Tsunami Warning Centers (NTWC). For each coast, the level of alert is determined by each country, from available international information and potential national assessments.

A tsunami warning system is based on automatic detections from an instrumental network. Earthquakes are the source of most of the tsunamis (e.g., National Geophysical Data Center/World Data Service: NCEI/WDS Global Historical Tsunami Database. NOAA National Centers for Environmental Information). The above-mentioned tsunami warning systems detect tsunamis generated by earthquakes. There are two main stages in the organization of such a warning. Firstly, upstream alerts to receive and process seismological data and sea level monitoring (including coastal tide gauge or deep ocean buoys), to detect a potentially tsunamigenic earthquake and to confirm and characterize the induced tsunami, and secondly, downstream alerts to the authorities. Forecasting systems can provide information on the impact due to the tsunami from pre-calculated models or rapid estimations.

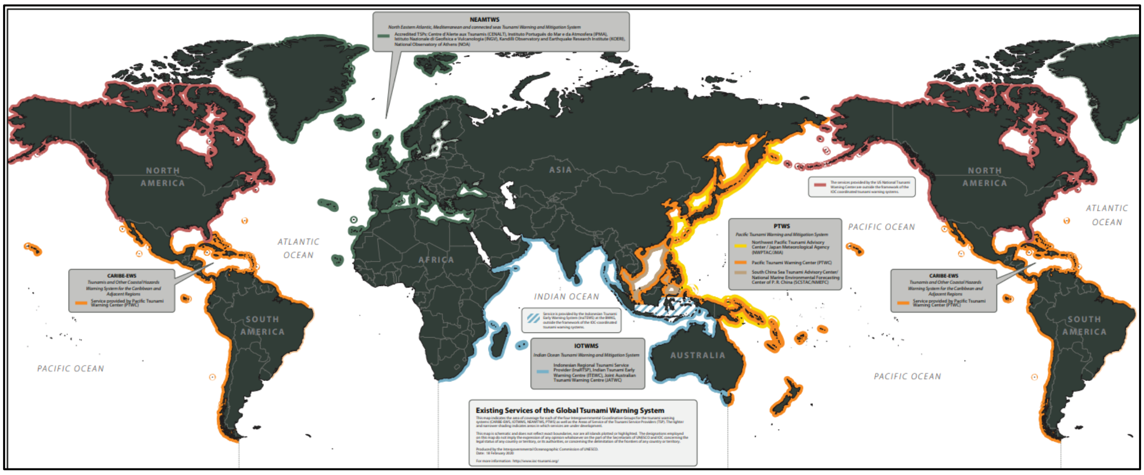


Figure 25: Organisation of the Global Tsunami Warning System
From www.ioc-tsunami.org

80% of reported tsunami were induced by earthquakes (e.g., Clouard et al., 2024), and tsunami warning systems respond to the detection of potentially tsunamigenic earthquakes and tsunamis at ocean scale. However, recent initiatives aim to rise to some challenges linked to the tsunami phenomenon, advances made possible by developments in tsunami understanding, modelling, and monitoring since the occurrence of the large tsunamis in 2004 in Sumatra, in 2010 in Chile or in 2011 in Japan (e.g., Williamson et al., 2020).

Firstly, it concerns near field rapid detection, especially useful when tsunamigenic structures lies close to the coast, e.g., close to subduction zones. Rapid near filed detection can concern the tsunami source of the early tsunami waves. Williamson et al. (2020) tests how a local GNSS dense network, could contribute to the rapid earthquake characterization for the Cascadia megathrust, enhancing the accuracy in characterizing the tsunami impact. Mori et al. (2022) or Wang et al. (2021) present reviews of recent progresses in tsunami forecasting and early warning in the near-field domain. Near field tsunami early warning is possible in few places where some dense array of offshore observational devices (e.g., ocean-bottom pressure gauges) can monitor some sea-level changes due to a tsunami. Thanks to data assimilation, the tsunami wavefield is estimated from real-time tsunami signal extraction.

For near-field forecasting, offshore tsunami observations can enhance conventional early warning methods. Moreover, for no seismic sources (e.g., volcanic activity, landslides) which are difficult to detect using an instrumental network, only sea-level monitoring could permit tsunami forecasting and early warning. However, near-source ocean-bottom pressure monitoring network are rare and only deployed in very few places (e.g., Japan, Figure 26), as soon as such network need to be dense enough in the source area. Such monitoring network are very expensive and difficult to deploy and to maintain. Such sea-level monitoring networks are a world apart from the European sea-level monitoring capacities.

As an example, Papadopoulos et al. (2020), evaluate the Mediterranean tsunami warning system's performance in a near-field context (i.e., a Mw 6.6 earthquake that occurred in Crete in 2020, inducing a small tsunami that arrived within 17' in southern Crete). They argue that the law accuracy of the initial earthquake parameters, the time of the alert and the lack of precision within the alert messages lead to an inadequate tsunami alert. These problems contributed to the low efficiency alert for some close forecast points.

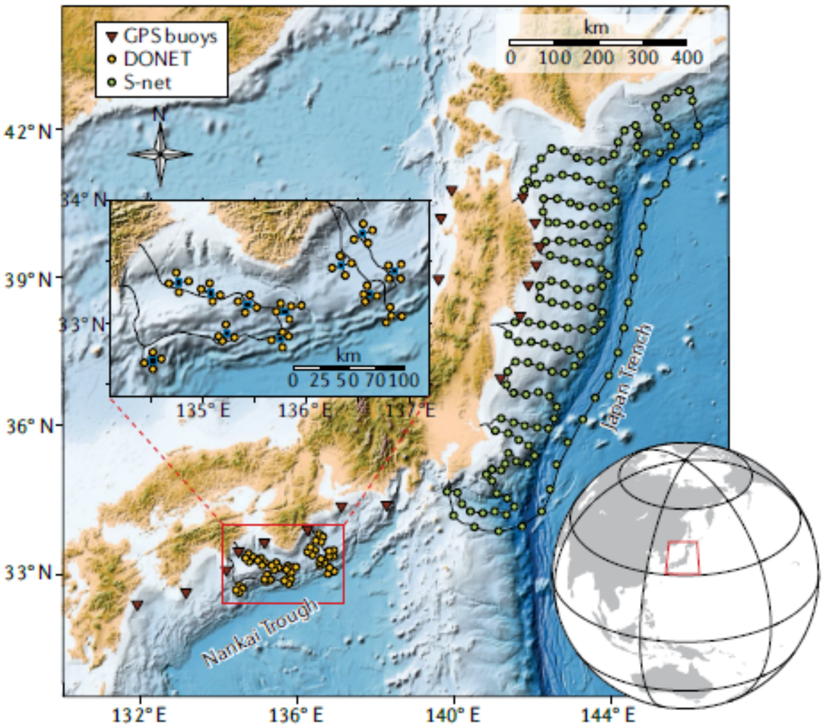


Figure 26: Ocean-bottom pressure monitoring network available in Japan
Rapid tsunami forecasts can occur within 3 minutes for the near-shore region (Mori et al. 2022).

Some examples of tsunami forecasting and warning systems are presented in the following pages. We focused on certain methods within the boundaries of **GOBEYOND** project (i.e., concerning the Atlantic or Mediterranean basins), or on methods compatible with the project's objectives.

3.3.1. ICG/NEAMTWS

The Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO) established the Intergovernmental Coordination Group for the Tsunami Early Warning and Mitigation System in the North-eastern Atlantic, the Mediterranean and connected seas (ICG/NEAMTWS) in 2005. The ICG contains also Working Groups (WP): the ICG and its Working Groups, WG1 (Hazard Assessment, Risk and Modelling), WG2 (Seismic and Geophysical Measurements), WG3 (Sea Level Data Collection and Exchange, including Offshore Tsunami Detection and Instruments), and WG4 (Advisory, Mitigation and Public Awareness). The NEAMTWS has a complex organization with different Member States designated agencies whose role may be both national and international or regional (e.g., providing information to the NEAMTWS).

The objective is to detect and handle seismically induced tsunamis that could propagate through the basins and to create early warning messages toward coasts, thanks to five national tsunami warning centres (as Tsunami Service Providers, TSP) covering the different areas of the basins and providing alerts to member States. Different components constitute the NEAMTWS.

The *Tsunami Service Providers* collect, record, process and analyse seismological data to provide the rapid initial detection of a possibly tsunamigenic earthquake before computing the arrival time in some pre-existing forecasting points. Sea level monitoring permit to confirm and eventually monitor the tsunami. Messages written from a decision-making process are disseminated to the Member States focal points and national warning centres. *Tsunami National Contacts*, designated officially in each Member State, represent their country in the coordination of the international tsunami warning and mitigation activities. *Tsunami Warning Focal Points*, 7x24 contact persons, designated by each Member State for receiving and relying on tsunami event information. Five Tsunami Watch Centers are covering the NEAM, hosted in France, Greece, Italy, Portugal, and Turkey, among them, the CENALT, the French Tsunami Warning Centre.

3.3.2. The CENALT

The Cenalt, the French Tsunami Warning Centre is operated by the French Commissariat à l'Energie Atomique (CEA).

3.3.2.1. State-of-the-art and objectives

The CENALT has been operating tsunami warning for France since 2012. It is part of the system coordinated by the UNESCO for the tsunami warning and mitigation for the North-Eastern and Mediterranean regions (NEAM). The CENALT provides to the French civil protection and to members states of the NEAM some messages in case of potentially tsunamigenic earthquake in the western Mediterranean Sea or the north-eastern Atlantic Ocean. The messages describe assessment of potential tsunami risk from seismological analysis, monitoring of sea level variations and numerical simulations of tsunamis.

3.3.2.2. Principles and elements of theory

The CENALT warning system includes different steps and techniques (Schindelé et al., 2015). As a typical tsunami service provider, the operational tools include a real-time seismological network for earthquake detection and characterization, a real-time sea-level monitoring networks for tsunami detection and its monitoring and tools for data processing and message dissemination. Moreover, precomputed scenario databases and tools for estimating the tsunami amplitude in case of an event permit to forecast potential tsunami impacts and arrival times. The aim is to disseminate threat messages to French authorities (and international warning centres) within 15 minutes in case of a potentially tsunamigenic earthquake, then tsunami detection confirmation or alert cancelling, and finally estimation of threatened area within 2 hours.

In case of an event, the warning system follows different steps:

Threat evaluation: a decision matrix permits to choose between 3 alert levels (information, advisory, watch) from a first detection and characterisation of an earthquake in the area of interest, depending on the earthquake's parameters (magnitude, depth), distance to the coast and to forecast points (pre-set points where a tsunami warning centre should provide tsunami arrival time and/or wave height). First estimation of tsunami travel time is automatically calculated for tsunami forecast points with a code (TTT, Tsunami Travel Times, Geoware®) using the Huygen's principle (Shokin et al., 1987) and included in the first alert message. This first message, evaluating a potential tsunamigenic earthquake and potential arrival time to forecast points is issued within 15 minutes.

Sea-level detection: To confirm that a tsunami generation occurred, or to cancel the alert, sea-level RT monitoring enables tsunami detection. The detection capacity depends on the network geometry. Sea level monitoring can come from tide gauges in harbours and pressure sensors on the sea floor. For example, in other basins, sea-level monitoring for tsunami warning purposed can imply Deep-ocean Assessment and Reporting of Tsunamis (DART), as for example in the Pacific Ocean. But in NEAMWS, no pressure gauge station is in operation.

Alert level refinement: After the first alert, the CENALT aim to estimate, within 2 hours, potentially impacted areas thanks to automatic tsunami modelling based on pre-computed scenario data base (Gailler et al., 2013). Such deterministic tsunami modelling considers uncertainties in tsunamigenic source and magnitude. Outputs include 3 offshore tsunami height maps representing the most probable, minimum, and maximum scenarios. The method implies first a pre-computed unit source data base (from the CEA hydrodynamic simulation code, e.g., Hébert et al., 2007) and an aggregation method to build a composite scenario from the unit's source, depending on the earthquake's parameters estimation.

3.3.2.3. Technological requirements

Continuous RT seismological network including CEA and other French reliable stations completed with foreign stations (e.g., Portugal, Spain, Italy, Tunisia and Germany, Figure 27). Continuous RT sea-level stations from the French Hydrographic and Oceanographic Service (SHOM) added by data from the neighbouring countries thanks to IOC (some availability delays). Specific tools to monitor the sea level networks. CENALT operate at a regional scale, dealing with events in the western Mediterranean Sea (Figure 28). Automatic processing is used in the first step of the alert, but operators present 24/7 are involved in the following steps of the warning system. Data transmission from satellite and telecommunication networks. Latency of 1-2 minutes for some sea-level monitoring stations. Alert communication following protocols supervised by IOC/UNESCO.

Figure 27: Distribution of RT seismic and sea-level networks used by the CENALT in 2015. From Schindelé et al. (2015).

Operating platforms for alert visualization and issuing exist at CENALT that is an institution dedicated to tsunami warning. In addition, protocols for alert dissemination are defined, in particular the official protocol coordinated in ICG/NEAMWS and national protocol for alert toward French authorities.

As for tsunami impact assessment there is no operating platforms, but the estimation of offshore tsunami height in predefined forecast points is computed. As a perspective development, Schindelé et al. (2015) propose the use of empirical amplification laws or high-resolution modelling in order to estimate the tsunami impact on the coastline (Figure 29). However, to estimate the onshore tsunami height, Gailler et al. (2018), proposed a rapid forecast method based on coastal amplification laws. The CENALT is a TCP, a national tsunami warning centre, included in the ICG/NEAMWS coordinated by IOC/UNESCO.

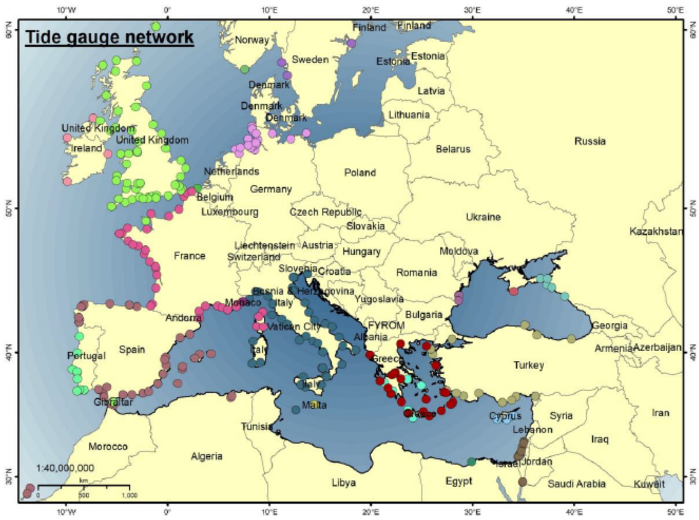


Figure 28: Tide gauges networks used in the NEAMWS.
From ICG-NEAMTWS 2019.

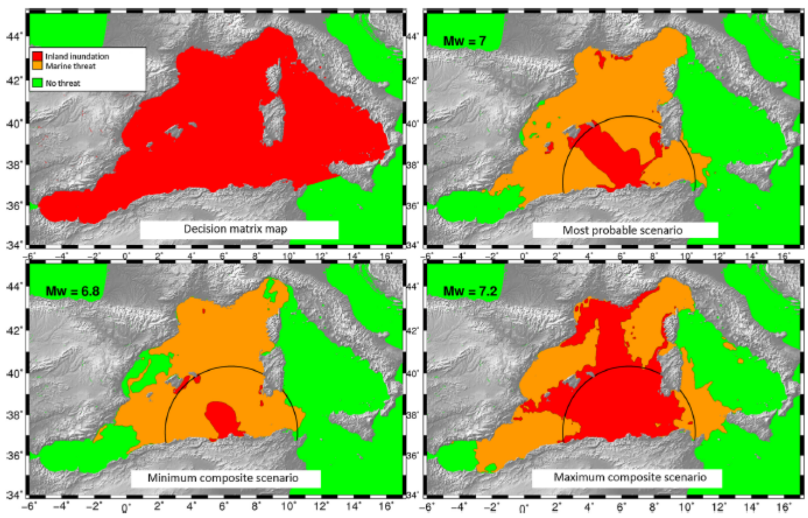


Figure 29: Forecasting outputs of the CENALT tsunami warning system for a scenario close to the northern African coast.
From Schindelé et al. (2015).

3.3.2.4. End users

Real time monitoring and analysis of seismicity and sea level. CENALT operates 24/7. The end users of the system are the French civil protection authorities, other tsunami warning centres, ICG/NEAMWS member States.

3.3.2.5. Pros and cons of the methodology

The CEA is responsible for both the seismic and tsunami alerts in France. It is an advantage for the alert capacity and the RT seismic networks monitoring that guarantee the continuity of the system. The CENALT belongs to the ICG/NEAMWS, managed by IOC/UNESCO, i.e., a robust system for detecting, monitoring, and forecasting tsunami induced by earthquakes at an ocean scale.

A limitation is that the tsunami warning system capacity is particularly depending on the monitoring networks. If potentially tsunamigenic earthquakes seem to be detectable thanks to the regional seismic RT network, their spatial distribution is inhomogeneous, leading to a variable accuracy in the source parameter determination. Moreover, only the sea level monitoring is performed using tide gauges, not equally and densely distributed in the NEAM area. No deep ocean buoys are available for tsunami detection in the area. The tsunami detection delay is strongly dependant on the sea level monitoring network, whereas the “small” size of the Mediterranean Sea is challenging in term of alert delay (a tsunami can cross the Mediterranean Sea in ~60-80 minutes), then it requires efficient detection capacities.

3.3.2.6. How will GOBEYOND take this to the next level?

Only seismic sources are considered, and near field is still challenging, even if some new approaches are emerging: among them, the transfer function method for coastal tsunami amplitude forecasting (Gailler et Hébert, 2023) or “deep learning approach for real-time tsunami impact forecasting in near field context” (Andraud et al., 2023). Onshore forecasting is out of the aim of the CENALT. An accurate modelling of the potential flooding induced by a tsunami needs high resolution models and good quality data sets. From existing data bases of HR tsunami modelling already published or available for some target areas (e.g. for the French SE coast including Nice: Fillippini et al., 2022; Nemati et al., 2019), it would be possible during **GOBEYOND** project, to implement tools of massive exploration of potential scenarios, based on real-time computed, earthquake source parameters and a pre-computed scenario, in order to retrieve the results in term of tsunami impacts where some simulations are available.

3.3.3. The Italian dual system

3.3.3.1. State-of-the-art and objectives

The Italian national warning system for seismic sources (SiAM) is composed by the CAT-INGV (Centro Allerta Tsunami dell’Istituto Nazionale di Geofisica e Vulcanologia), one of the NEAMTWS TSP (Tsunami Service Provider since 2016) and dedicated to the whole Mediterranean region, and by a local tsunami warning system dedicated to the monitoring of tsunamis generated by volcanic slides on the Stromboli volcano (e.g., Selva et al., 2021). As one of the regional NEAMTWS TSP dedicated to regional seismic sources has already been described previously, this section will focus on the description of the TWS of the Stromboli volcano. For submarine landslide, there is no regional tsunami warning system, as they are organized for earthquakes, but some early warning systems are deployed for some site-specific landslides, as for example in Norway were some identified potentially rockslides are monitored 24/7 with in situ instrumentation (Kristensen et al., 2020). Both sea-level changes and specific tsunami sources can be monitored, but monitoring the sources, when they are well defined permit to optimize the alert time. In the case of the Stromboli tsunami warning system, tsunami detection and source monitoring tools are combined.

The Stromboli Island is an active volcano whose activity can enhance massive landslides, from a well-known unstable sector, that can induce tsunami. Such tsunamis can affect neighbourhood coasts (Maramai et al., 2014). Large mass failure (and then tsunamis) may be triggered during flank eruptions, effusive eruptions, or paroxysmal explosions. The tsunami warning system at Stromboli includes firstly a multi-parametric network whose aim is to monitor anomalies that can testify to changes in volcanic activity, especially transitions between different eruptive phases (e.g., seismo-acoustic stations, thermal cameras, tiltmeters, SAR interferometry). In parallel, two elastic beacons are located offshore the more instable area to be able to detect tsunami waves at their early age (hydrostatic pressure, hydroacoustic temperature, GNSS and tiltmeters sensors, power supply equipment and radio transmission system), and to transmit the data to the local operational centre for the civil protection (COA, Advanced Operational Centre). Finally, an acoustic warning system can be enhanced manually or automatically (in case of a tsunami wave detection) which is interconnected to a dedicated VHF radio network.

3.3.3.2. Principles and elements of theory

The tsunami detection algorithm is automatic, however the sea conditions are tuned from a simulation database and tested with two criteria: surface wave dispersion and STA/LTA. The activation of the acoustic TWS is automatic from this detection. The evacuation plan is based on the tsunami inundation extension reported after the 30 December 2002 tsunami, the largest and best documented event. Hazard quantification is deterministic in this challenging context. The tsunami source characteristics and dynamics are difficult to forecast. Moreover, specific conditions lead to use relevant simulation tools, as the source considered is a subaerial landslide, close to the shoreline, and the bathymetry is steep and irregular. Benchmarked models were compared to identify accurate and efficient models. Non-hydrostatic models, computationally more expensive allows for a better description of the near-source tsunami, however, the source characterization remains the largest source of uncertainty in the model.

Two small tsunamis were detected in July and August 2019 due to paroxysmal explosions that enhanced pyroclastic flows, after a first successful test in April 2019. The lead time for warning depends on the dynamics of the event (e.g., if the event is sudden, the inland monitoring networks can be unable to detect precursors). In August 2019, the tsunamigenic pyroclastic flow reached the sea ~35 minutes after the eruption, the tsunami was generated ~60 minutes after the volcanic explosion (Selva et al., 2020).

3.3.3.3. Technological requirements

Monitoring of the activity of the volcano is done through a multi-parametric network including seismic-acoustic stations, thermal cameras and tiltmeters. Monitoring of the sea-level is done through two elastic beacons located offshore the preidentified source (hydrostatic pressure, hydroacoustic temperature, GNSS and tiltmeters). The spatial scale is mostly local, or “ad hoc” TWS, but warning can concern neighbourhood coast.

Automatic data processing of the of the sea-level offshore is used to monitored instability, however, sirens can be activated manually, in case of human observation of some pyroclastic flow reaching the sea. This was the case in August 2019 by the local civil protection personnel. The multi-parametric volcanic activity monitoring permit to the local civil protection to identify Volcanic Alert Levels. Data transmission in real time from radio transmission system is done to the local operational centre for the civil protection (COA, Advanced Operational Centre). Alert communication is provided through either automatically or manually enhanced acoustic warning system, connection with a dedicated VHF radio network.

3.3.3.4. Operational platforms for alert visualization and dissemination

For operating platforms, there is a local dedicated centre operated by the civil protection with protocols for alert dissemination. The impact assessment consists of identified zones to be evacuated in case of some kind of volcanic activity or in case of an automatic warning. Evacuation routes guide people in case of an event. The potentially impacted areas are determined from the 2002 tsunami that impacted Stromboli Island. Impact modelling remains challenging and to be enhanced (cf in the following section). The civil protection's operational centre is installed in the Island and in charge of the TWS.

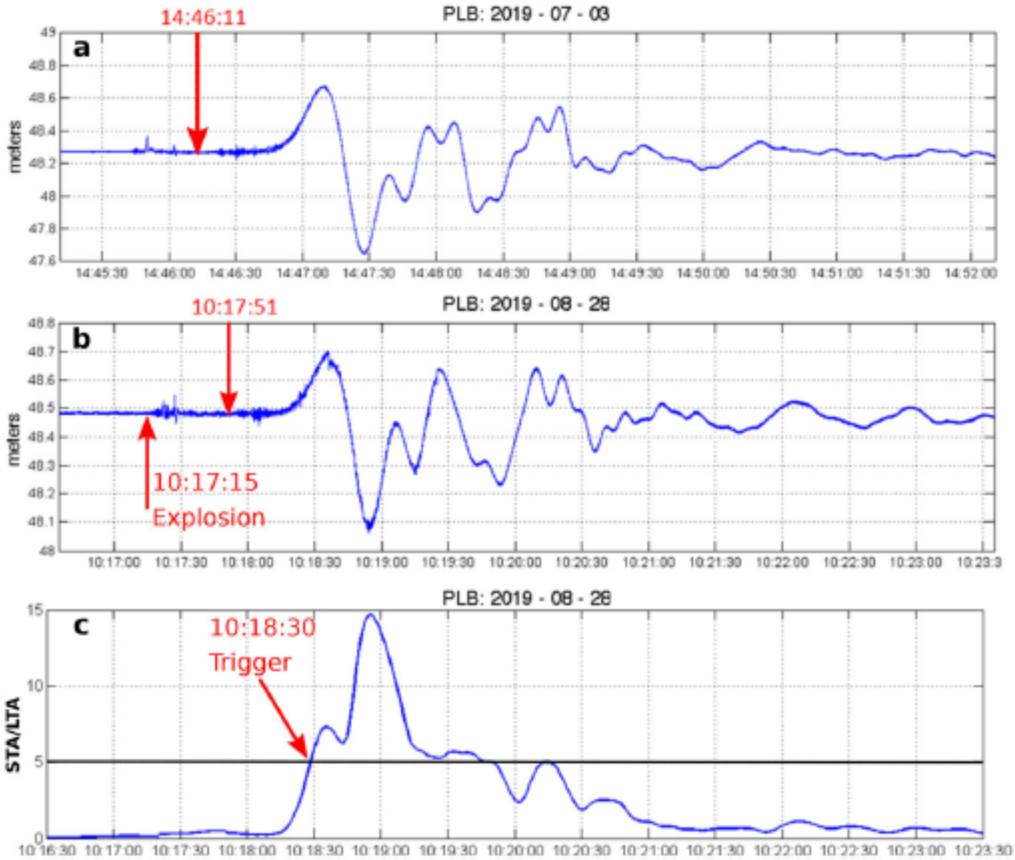


Figure 30: Tsunami signals registered at an elastic beacon deployed offshore the tsunami source. a/ and b/ represent the signals for two events that followed two proximal explosions of the volcano in 2019. c/ show the automatic detection of the tsunami that can enhance the warning. From selva et al. (2020)

3.3.3.5. Validation

The detection of two small tsunamis by the Stromboli TWS that occurred in 2019 is described in Selva et al. (2020, Figure 30).

3.3.3.6. End users

Tsunami detection can be automatic in real time from the offshore elastic beacons, or manual from the detection and observation of an increasing volcanic activity. The end users are the civil protection, municipality and public.

3.3.3.7. Pros and cons of the methodology

The installation of monitoring networks dedicated both to the monitoring of the tsunamigenic sources (volcanic activity, landslide) and of the sea-level lead to an efficient “ad hoc” tsunami warning system. Moreover, it remains an “ad hoc” TWS, and highly dependent on the monitoring networks.

Tsunami numerical modelling is challenging in such a context (i.e., complex tsunamigenic process, near-source context, presence of dispersive waves). Both tsunami generation and propagation modelling need appropriate tools that can be complex or computationally expensive. A large uncertainty in the source behaviour (and modelling) remains the largest source of uncertainty.

GOBEYOND could potentially take this to take this to the next level though HR modelling of flooding and damages could improve the tsunami impact modelling, by extending the range of simulation tools used.

3.3.4. VONUT - VOlcano Notice for tsunami Threat

3.3.4.1. State-of-the-art and objectives

Classical TWS dedicated to tsunami induced by earthquakes of local TWS such as the Stromboli one is based on networks that monitor both potential tsunamigenic sources and sea-level perturbation. Recently, several volcanic events illustrated the need of including volcanic sources in the tsunami warning procedures, especially the 2018 Anak Krakatau flank collapse and the 2022 Hunga Ha’pai eruption). However, due to the complexity and variability of the potential tsunamigenic sources associated to volcanic activity, this objective is challenging both regarding the monitoring networks and the forecasting needs, as illustrated by the Stromboli TWS.

Clouard et al. (2024) proposed a bulletin (« VONUT ») for volcanic tsunami that could be written by the Caribbean volcano observatories in case of a potential volcano-induced tsunami threat (Figure 31). Such bulletin, close to the one written by volcano observatories in case of volcanic ash toward civil aviation, should be issued by local volcanic observatories to the regional TSP, informing it with a potentially tsunamigenic change in the volcano activity, in absence of a tsunami dedicated monitoring network.

3.3.4.2. Principles and elements of theory

No modelling or forecasting tsunami impact exists at this stage. The level of alert is determined by the local observatory, following the level of volcanic activity in case of a potentially tsunamigenic phenomenon. The level of volcanic activity is determined by the local dedicated observatory, based on their expertise and monitoring networks (GNSS, seismometers, etc). The spatial scale of operation is local including neighbouring Islands. Both automatic and manual data processing is used for the monitoring networks of the volcanic activity. Data transmission of alerts depends on the monitoring network or local observatory. Alert communications are issued from the observatory toward the regional Tsunami Service Provider (TSP) following an alert protocol.

VONUT is not yet operational. However, ICG/CARIBE-EWS suggests that the TSPs include the VONUT bulletin in the TWS procedures and also to implement this tool with the different volcanic observatories of the Caribbean basin. Impact assessment is not yet available. Both the complexity and variability of potentially tsunamigenic sources in such a volcanic context and the lack of knowledge of structures lead to difficulties in modelling tsunami impact from volcanic sources.

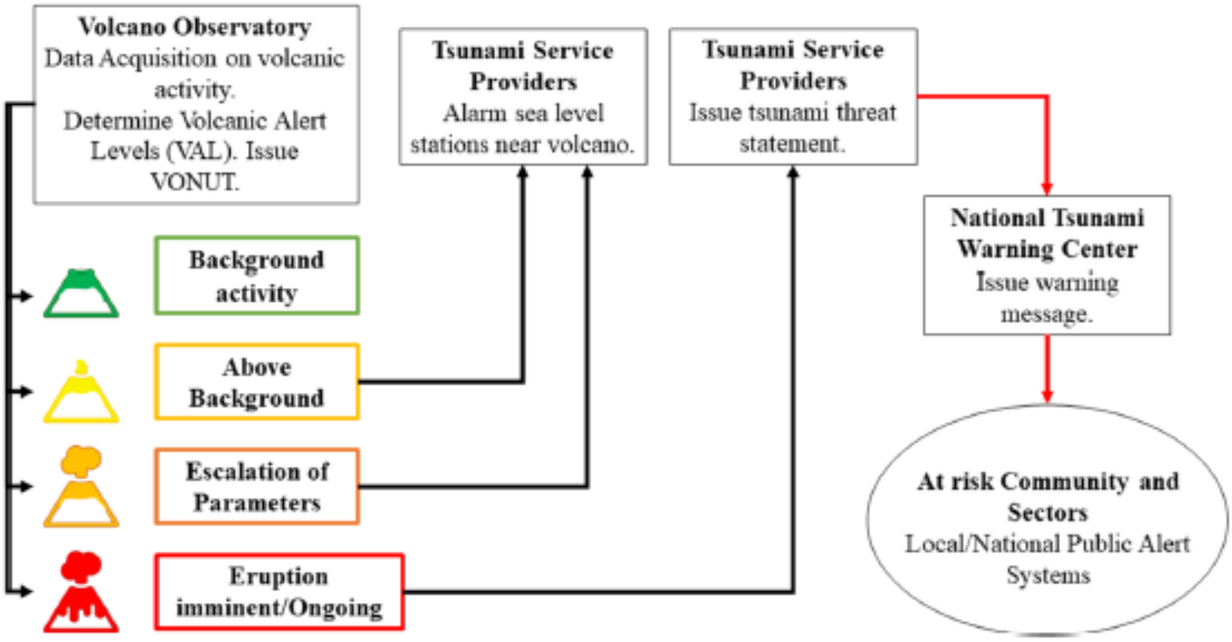


Figure 31: Proposed system of alert for tsunami induced by volcanic activity. From Clouard et al. (2024).

3.3.4.3. Validation

Clouard et al. (2024), and von Hillebrandt-Andrade et al. (2023) describe the VONUT method. VONUT has been tested during the annual tsunami exercise “Caribe Wave 2023” based on a scenario of flank collapse of the Mount Pelée in Martinique Island.

3.3.4.4. End users

The system is not yet in use, but the end users would be Tsunami Service Providers, National TWC, national and local authorities, and the public

3.3.4.5. Pros and cons of the methodology

Tsunami warning procedures for a volcanic crisis are challenging due to the specificity and to the lack of detection networks in the vicinity of numerous potentially active volcanoes and also due to the limitation of the capacity of modelling the tsunami impact generated by complex and only partially known processes. Another difficulty is linked to the variability of the tsunamigenic processes that can occur during a volcanic crisis. Sea-level monitoring that could detect tsunami should be considered and deployed.

However, the VONUT bulletin, is a simple way of considering the tsunami in case of volcanic changes of activity. It is based on a current bulletin emitted by volcanic observatories in order to evaluate the volcanic ash warnings to aviation (i.e., both volcanic observatories and authorities are used to such bulletins). The implication of local volcanic observatories in the TW procedure should lead to an efficiency in the phenomenon understanding. Finally, the information of the population in case of some change in the level of volcanic activity is important for educational purpose.

Blocking factors for progress are the deficiency in sea-level networks. Tsunami impact or risk assessment for volcanic sources should be proposed for each active volcano. In the **GOBEYOND** project we aim to integrate some volcanic sources in tsunami modelling databases.

3.4. Landslides

Landslide early warning systems (LEWS) and rapid response strategies aim to detect **precursors** to landslides and provide timely alerts to at-risk populations, allowing for evacuation and other preparedness measures. Landslide monitoring involves the use of various sensors and techniques to detect changes in slope stability and ground conditions. This may include ground-based instruments such as inclinometers, piezometers, and GPS, as well as remote sensing technologies like satellite imagery and LiDAR. Like the volcanic hazard, the early warning for landslide is meant to issue the alert before the event occurrence based on the detection of precursory phenomena that are analysed by monitoring networks to identify potential landslide triggers, such as rainfall, ground shaking, or soil moisture changes. Weather forecasting and rainfall monitoring are the basic indicators for predicting rainfall-induced landslides. The meteorological data, including rainfall intensity, duration, and spatial distribution, are continuously monitored in real-time to assess landslide potential. Risk assessments and hazard mapping are generally available for areas susceptible to landslides based on geological, topographical, and hydrological factors. This information is used in the aftermath of a landslide phenomenon to evaluate the spatial extents of its impact on the territory and communities.

Amongst EWS, territorial EWS (Te-EWS) developed at regional, national, and worldwide scales are gaining increasing attention among stakeholders (Piciullo et al., 2018; Guzzetti et al., 2020). In particular, mountain regions have strongly benefited from recent advances in meteorological data acquisition for observation, process-understanding, and forecasting, with direct implications for prevention of natural hazards induced by heavy rainfall and snow episodes. Guzzetti et al., 2020, has analysed different Te-EWSs implemented in the world, through different features: the geographical location, the landslide and rainfall data considered, the threshold models used, the design of EWS considering the specialization, the operational framework, the advisory systems, the implementation, and the performance evaluation. They propose some recommendations for further development or improvement of EWSs and indicate that still many areas with numerous fatal landslides are not covered by Te-EWSs. Most of the systems use information from rain gauge networks, meteorological models, weather radars, and satellite estimates, and their forecasting models are based on rainfall thresholds, distributed slope stability models, and soil water balance models.

3.4.1. Norwegian LEWS

3.4.1.1. State-of-the-art and objectives

The Norwegian LEWS uses (i) a complex set of measurements obtained by a national network of monitoring stations; (ii) a suite of numerical forecast models; (iii) a set of heuristic thresholds; and (iv) information on landslide susceptibility. This EWS concerns rainfall and snowmelt induced landslides, including shallow translational slides, channelized debris flows, debris avalanches and slush flows.

3.4.1.2. Principles and elements of theory

The forecast weather consists of two meteorological models: The short-term AROME MetCoOp forecast model (Müller et al., 2017), at 2.5 km × 2.5 km resolution, produces 3 and 24-h weather forecasts and is used for the first three days of the landslide forecast. The long-term ECMWF forecast model, at 9.0 km × 9.0 km resolution, produces 24-h forecasts and is used for the longer period forecasts, up to nine days.

Then, the HBV hydrological model (Bergström, 1995; Beldring et al., 2003) is used to forecast river runoff, snowmelt, groundwater, soil saturation, and soil frost. In addition, S-Flow groundwater simulation model is applied: this one-dimensional soil water and heat flow model simulates water and heat dynamics in a column of layered soil covered by vegetation.

Then several thresholds have been tested, based on different hydrogeological variables obtained from HBV model. A statistical analysis has then been performed, based on landslide inventory, (Colleuille et al., 2010; Cepeda et al., 2012; Cepeda, 2013a, b; Boje et al., 2014b). The best thresholds were obtained when using the relative water supply (percentage of annual mean) and the soil water saturation degree. Minimum, average, and maximum thresholds were defined through expert judgment, analysing information on 206 historical landslides. A quantitative evaluation of the performance of the Norwegian LEWS was conducted for the 4-year period 2013–2017 and revealed an overall rate of correct daily assessments of over 95%, including days when the weather was good and no landslide was expected (Krøgli et al., 2018). A survey among users of the forecasts in the same period yield positive feedback (Krøgli et al., 2018).

The assessments and updates are realised at least twice daily. The forecast and advisory covers three days and is valid 24 h.

3.4.1.3. Technological requirements

The monitoring network consists of ~ 400 meteorological stations that measure hourly and daily precipitation, temperature, wind speed and direction, and snow coverage and depth, ~ 400 hydrological stations that measure river discharge, and snow depth and coverage, and ~ 80 hydrogeological stations to obtain point groundwater measurements.

This LEWS is applied at the Norway scale, using national thresholds. Later, regional thresholds have been introduced, to consider the spatial variability of soil saturation and soil moisture conditions. The LEWS updates daily a national assessment of landslide hazard at the regional scale (i.e., for each county and/or group of municipalities in Norway) for rainfall and snowmelt induced landslides.

The daily landslide hazard assessment is performed by a forecaster who uses forecasted thresholds, forecasted hydrometeorological parameters, information from real-time observations, knowledge on historical events and regional susceptibility, and personal experience. The assessments and updates are published on a dedicated website at least twice daily. Each landslide forecast and advisory covers three days and is valid 24 h. The system delivers updates to national and regional stakeholders.

The forecast is provided within four levels of increasing warning level, and is communicated to the public through a bulletin, in Norwegian, and since January 2018 also in English. Since early 2017, concerned citizens can subscribe to obtain advisories for specific natural hazards, including landslides, notified via text messages or e-mails.

3.4.1.4. Operational platforms for alert visualization and dissemination

Xgeo.no is a decision-making tool used by forecasters for snow avalanches, landslides, and floods. The portal shows daily observations and forecasts for meteorological and hydrological conditions as thematic maps and timeseries data. The maps, show the conditions for each day, and for 9 days ahead.

Landslide specialists use this tool during the daily evaluation to visualize, for example, real-time measurements, weather forecast, threshold values predictions, water supply and groundwater simulations.

This EWS is developed as a joint initiative across public agencies between The Norwegian Water Resources and Energy Directorate (NVE), the Norwegian Meteorological Institute (MET), the Norwegian Public Road Administration (NPRA) and the Norwegian Rail Administration (Bane NOR).

3.4.1.5. End users

The development of this LEWS began in February 2010; then, after an experimental phase in January 2012, the system went operational in October 2013 (Figure 32).

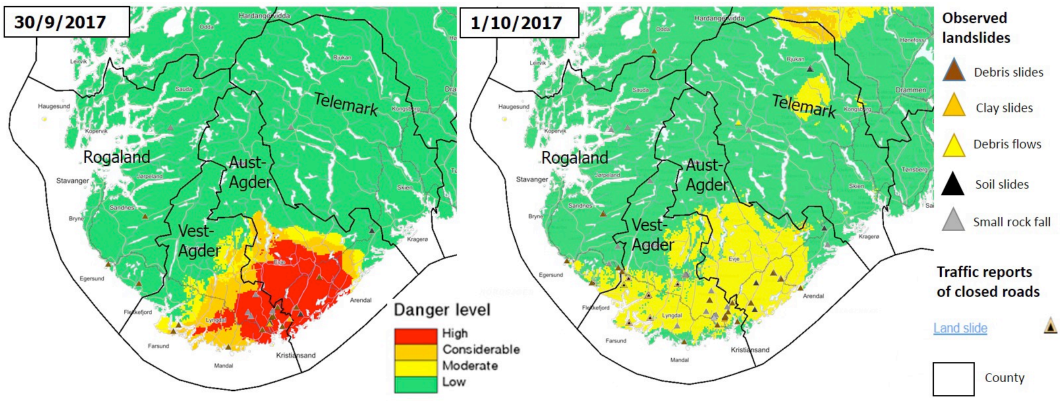


Figure 32. Landslide threshold maps based on observed values

Regional landslide hazard threshold for Southern Norway and distribution of landslide events. Closed roads due to landslides are also viewed in the same map. From Krogli et al., 2018.

3.4.2. The Tuscany (Italy) LEWS

3.4.2.1. State-of-the-art and objectives

This regional EWS has been developed in Toscana region, Italy. It is mainly based on I–D rainfall thresholds, that have been defined on different areas, to consider spatial variability of the meteorological and hydrogeological conditions.

3.4.2.2. Principles and elements of theory

This EWS is based on I–D rainfall thresholds (Segoni et al., 2014b), defined using the approach and methodology of analysis presented in Segoni et al., 2014a. The EWS combines weather forecasts and real-time rainfall measurements obtained by a network of rain gauges.

To account for the high spatial variability of the rainfall–landslide empirical relation through this territory, statistical ID thresholds have been defined for 25 geo-hydrological alert zone in the Region. They have been defined based on rainfall records and landslide inventory (more than 3000 landslides in Tuscany between 2000 and 2013). Every hour and for each rain gauge, the LEWS cumulates the measured and the forecasted rainfall for 6, 12, 24, and 48-h periods to define four landslide scenarios.

For each of the 25 alert zones, every rainfall event was classified as:

- True positive (TP or correct prediction: some landslides were triggered in relation to a threshold being exceeded),
- True negative (TN: the threshold was not exceeded, and no landslide was triggered),
- False positive (FP, or false alarm, i.e., threshold exceeded without landslides triggering),
- False negative (FN, or missed alarm: the threshold was not exceeded, but some landslides were triggered).

3.4.2.3. Technological requirements

The technological requirements for the Tuscan LEWS encompass the following setup:

- Sensor networks:

LAMI meteorological model (Cacciamani et al., 2002) provides quantitative rainfall forecasts provided by the COSMO I5/I7 weather model at 7 km × 7 km resolution, with 6, 12, 24 and 48 h lead times. The EWS also uses near real-time rainfall measurements taken by 322 automated rain gauges, corresponding to an average density of one gauge every ~ 71 km^2.

- Spatial and temporal scale of operation:

This EWS has been applied at a regional scale, in all Tuscany region (23 000 km^2/, Italy). Most of these instruments measure rainfall at hourly time steps.

- Automatic/Manual Data processing and analysis:

A real-time warning system service is implemented: every 15 min a script establishes a connection to the FTP (File Transfer Protocol) server, checks for the presence of updated CSV files, downloads them, and stores the data in a local DBMS (database management system). The updated CSV file contains information such as name, geographical coordinates and elevation of each active rain gauge belonging to the network, and the hourly rainfall intensity measured in millimetres per hour.

Then, for each gauge station, local rainfall forecast values are summed to the real-time measurements and the cumulative rainfall amount is estimated for four different future scenarios (6, 12, 24 and 48 h in advance). With the help of a purposely developed WebGIS interface, it is therefore possible to assess whether the threshold will be exceeded or not with a suitable lead time to ensure an effective early warning capability.

- Data transmission and alert communication:

An alert is raised in a given alert zone if at least one of its rain gauges exceeds the threshold. For each alert zone, a landslide advisory is issued when the measured and the forecasted rainfall in at least one rain gauge exceeds the corresponding threshold, for any of the four scenarios.

Civil protection personnel consult the forecasts through a proprietary web-based interface and use them to prepare and publish daily bulletins showing landslide critical levels in each alert zone, adopting a 4-level advisory scheme.

3.4.2.4. Operational platforms for alert visualization and dissemination

The Tuscany LEWS developed a WebGIS with the purpose of providing the civil protection personnel with a straightforward tool for both the forecasting and the real-time monitoring of the temporal evolution of the hazard level associated with rainfall-induced landslides.

This WebGIS continuously connects to the database (60 s refresh time) and, in its basic view, displays the status of all the rain gauges of the network using different colours depending on the value of cumulative rainfall. The possible states of the system are:

- Inactive (no data available because of malfunctioning or temporary communication breakdown).
- No rain (no rain recorded in the last X hours, where X represents the no rain gap of the alert zone).
- Ordinary (rainfall below the threshold).
- Alert (rainfall above the threshold).

According to the regional laws and the civil protection procedures, the Tuscany Region Functional Center is in charge of providing rainfall forecasts, with 6, 12, 24 and 48 h lead times, which are estimated using the LAMI meteorological model (Cacciamani et al., 2002). It is also in charge of maintaining the network and collecting and storing all the measured data on a secure FTP (File Transfer Protocol) server.

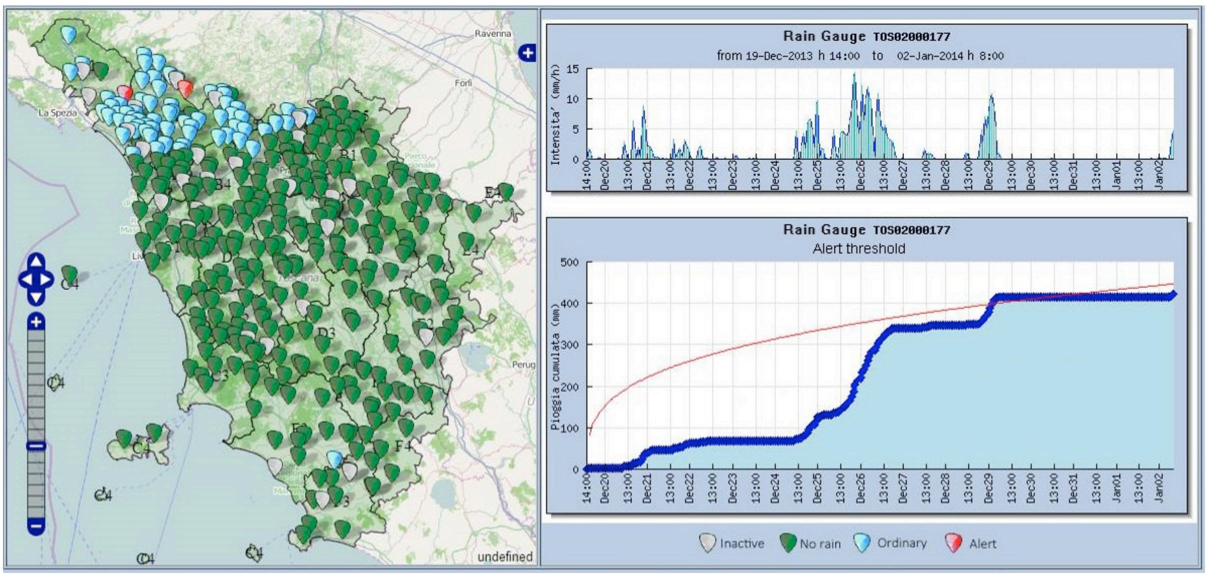


Figure 33. The December 2013 rainfall event that struck northwest Tuscany

3.4.2.5. Validation

Figure 33 shows the specific case of the December 2013 rainfall event that struck northwest Tuscany. According to official civil protection reports, the event triggered an unspecified number of landslides in alert zone A3, and two rain gauges just exceeded the alert threshold. In addition to the spatial accuracy, in this case the timing of the alert was in good agreement with the ground truth as well: according to reports, all landslides occurred between 28 and 29 December, and this is approximately the time when the threshold was exceeded.

3.4.2.6. End users

After a 2-year test period, the EWS was operated by the Tuscany Civil Protection Authority and used for hazards related to landslides.

3.4.3. The Catalan (Spain) LEWS

3.4.3.1. State-of-the-art and objectives

The Catalan Landslide Early Warning System (LEWS) originated with the work of Berenguer et al. (2015) and was initially implemented in the Catalan Pyrenees. Subsequently, Palau et al. (2020, 2022) expanded and refined the system to cover the entire Catalonia. Currently, it is running in real-time on the CRAHI-UPC servers and is being evaluated in real time in collaboration with the Cartographic and Geological Institute of Catalonia (ICGC). This system integrates two key components within a level warning matrix. The first component is a 30-meter-resolution susceptibility map, which remains static over time, providing a foundational understanding of the landscape's predisposition to landslides. The second component is high-resolution real-time rainfall estimates, constituting the dynamic aspect of the system. Together, these inputs generate a qualitative warning level map each time new rainfall information becomes available.

3.4.3.2. Principles and elements of theory

The determination of landslide warning levels within the Catalan system involves an integration of susceptibility and rainfall information through a warning level matrix (Figure 34).

To generate the susceptibility map, key inputs are sourced from two primary datasets. The slope angle is derived from the 5-meter resolution digital elevation model (DEM) of Catalonia (ICGC, 2013), while land cover data (LULC) is obtained from the Map of Soil Coverage of Catalonia (CREAF, 2009). Utilizing a fuzzy logic approach that combines these inputs, the classification yields four susceptibility categories: "very low," "low," "moderate," and "high".

The rainfall hazard assessment module uses high-resolution accumulation products (1 km and 30 to 60 minutes) such as those obtained from quantitative precipitation estimation (QPE) or by radar-rain gauges blending. The Intensity-Duration (ID) curves proposed by Palau et al. (2020) establish the rainfall thresholds to evaluate the landslide-triggering potential of the rainfall situation. Resulting in four rainfall hazard levels: "very low," "low," "moderate," and "high." Thereby, landslide events are currently forecasted in real-time because only rainfall observations are acting as inputs. Including data from precipitation forecasts is an improvement to be made within the current methodology.

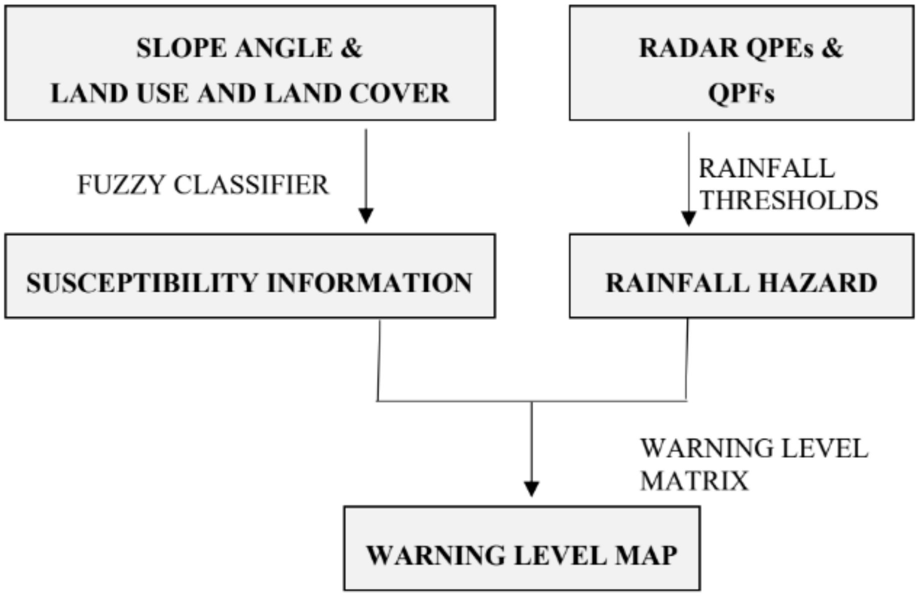


Figure 34. Scheme of the current LEWS of Catalonia. Adapted from Palau et al. (2020).

The determination of the warning level is done through the warning level matrix, combining the susceptibility class and the rainfall event magnitude within each cell of the domain. This process yields a qualitative warning level for each cell, categorized as "very low," "low," "moderate," or "high."

Carrying out a performance evaluation is crucial for any LEWS. To achieve a reliable evaluation, landslide inventories serve as essential references, therefore these inventories ought to be comprehensive in both space and time. Recognizing the uncertainties and imperfections in the inventories, Palau et al. (2022) carried out an evaluation on how well the warning map was able to separate points with landslide observations from points where landslides had not been observed. For evaluation purposes of the Catalan system, a landslide warning is thought to be issued when the warning level is equal or above moderate. See Palau et al. (2020, 2022).

Like the LEWS performance assessment in Rio de Janeiro-Brazil (Calvello & Piciullo, 2016) and Norway (Piciullo et al., 2017), the real-time application of the Catalan EWS included carrying out a long-term assessment of the issued landslide warnings using the Event, Duration Matrix, Performance (EDuMaP) method. The main difference between the EDuMaP and the previous method is that EDuMaP offers a deeper, more comprehensive evaluation by analysing additional landslide characteristics (e.g., occurrence, duration. See Tapia-Hurtado, 2023).

3.4.3.3. Technological requirements

The technological requirements for the Catalan LEWS encompass the following setup:

- Sensor networks: Comprises approximately 200 rain gauges and radar rainfall estimates derived from the volume scans of the Meteorological Service of Catalonia's (SMC) three radars.
- Scale of operation: The Catalan LEWS currently operates at a temporal resolution of 60 minutes for rainfall observations and a spatial resolution of 30 m (which are aggregated over subbasins and municipalities) covering the entire Catalan region.

- Data processing: Automated data processing and analysis mechanisms are integrated into the Catalan LEWS, enabling real-time functionality. The system generates a qualitative warning level map each time new rainfall observations become available.
- Data transmission and alert communication: Rainfall data are collected at the UPC servers from the Meteorological Service of Catalonia and are disseminated to the ICGC through a web-based platform and automatic email in the framework of the contract for collaboration in the development of the Catalan system.

3.4.3.4. Operational platforms for alert visualization and dissemination

The already mentioned LEWS has a password-protected platform in the framework of the cooperation between UPC and ICGC, which showcases rainfall events and their corresponding landslide warning levels. Currently, there is one designated person from ICGC that receives by email an alert when the warning level becomes moderate in a county for the first time.

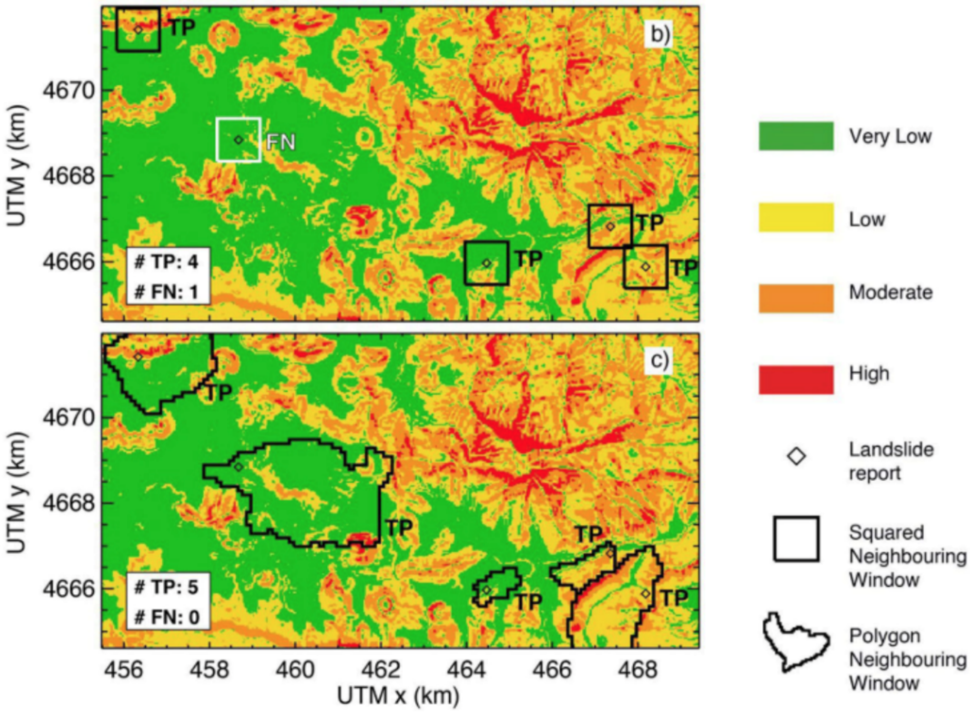


Figure 35 Fuzzy verification at an area of Catalonia on 23 January 2020

Verification applying b) 1-km, and c) subbasins neighbouring windows. The black diamonds represent the location of the landslide observations. The polygons and squares are the neighbouring windows. TP stands for true positive, and FN for false negative. All the grid cells with "Moderate" or "High" warnings outside the neighbouring windows are false positives. The pixels outside the neighbouring windows with "Very Low" and "Low" warnings are true negatives. Retrieved from Palau et al. (2022).

3.4.3.5. Validation

As examples of validation, two studies based on the performance evaluation of the Catalan LEWS in different scenarios are presented:

Palau et al. (2020) presented the extension of the EWS to the region of Catalonia and examined the influence of mapping units on the performance of the system. It focused on historic shallow slides and debris flows that occurred between April and October 2010 in the Pyrenees and Pre-Pyrenees regions. The validation specifically targeted two catchments, Rebaixader and Erill, prone to the occurrence of debris flows and with a monitoring system in place. The LEWS successfully associated reported and forecasted events with intense rainfall episodes. However, in some cases it failed to issue warnings, especially when the triggering rainfall was too weak.

In another study evaluating the Catalan LEWS, Palau et al. (2022) applied a fuzzy verification framework to analyse the performance of the system during the Gloria storm (20 to 23 January 2020). Various neighbouring window sizes (30-m, 500-m, 1-km, 2-km, 10-km, subbasins, and municipalities) and time windows (48-h and 96-h) were studied. Results indicated that when analysing large neighbouring windows, the system successfully forecasted 83% of landslide events. The improvement in skill scores was observed between window sizes 500 and 1000 m, suggesting that the LEWS effective resolution is around those ranges. A representation of the fuzzy verification process for two neighbouring windows is presented in Figure 35 alongside visual examples of true positives (TP) and false negatives (FN) during the evaluation.

3.4.3.6. End users

The operational status of the Catalan LEWS has been running in real-time since October 2022. Operating continuously, the system generates a qualitative warning level map, classifying the warnings into levels: "very low," "low," "moderate," and "high." This real-time capability ensures that the warning levels are reflective of the current rainfall observations.

At present, the main end user is the ICGC. The system's outcomes allow them to stay informed about the landslide warning levels reached during rainfall events, as part of their operational responsibilities. The collaborative efforts between these institutions play a vital role in maintaining a responsive system and extending its functionalities.

3.4.3.7. Pros and cons of the methodology

The methodology employed in the Catalan LEWS offers several advantages. Firstly, it is the system's simplicity and its, generally, easily found inputs, which enables the possibility of being replicated in other areas, or even in larger areas (currently it is applied on a regional level).

Another one is the utilization of high-resolution quantitative precipitation estimates (QPE) as inputs, which enhances the depiction of rainfall field variability, providing a nuanced understanding at high spatiotemporal resolutions (Palau et al., 2020). The fuzzy logic approach, as explained by Palau et al. (2020), proves effective in modelling the non-linear behaviour of variables while considering the uncertainties in input parameters and landslide inventories. This approach stands out for its capability to consider factors beyond slope angle, incorporating information on sediment availability and vegetation presence, as recognized by Persichillo et al. (2017); and Pisano et al. (2017).

The main limitations of this methodology. The reliance on radar QPE requires meticulous processing to ensure the quantitative accuracy of rainfall products, as highlighted by Palau et al. (2020). Global or local biases in the rainfall field may lead to false positives and false negatives. Additionally, obtaining high-resolution information on geotechnical variables directly linked to landslide occurrence at a regional scale is quite difficult. Thus, susceptibility characterization resorts to morphological parameters derived from DEMs and, occasionally, geological and land cover information (Chevalier et al., 2013; Kirschbaum et al., 2016).

Collecting accurate landslide inventories is a challenging task because they are usually compiled from aerial photographs, remote sensing data, field surveys, local reports, newspaper accounts, and crowdsourcing efforts (Galli et al., 2008; Guzzetti et al., 2012). Thus, these inventories are incomplete and biased to events that affected urban areas or infrastructures (Ardizzone et al., 2002). Additionally, regions highly susceptible to landslide events are often situated in inaccessible mountainous areas, resulting in underreported incidents due to the lack of infrastructure and roads affected.

These limitations compromise the spatial and temporal accuracy of landslide inventories, impacting performance evaluations (Palau et al., 2020, 2022). Moreover, the limitations extend to the availability of satellite imagery with coarse spatial resolution and infrequent acquisitions by very high-resolution satellites, constraining the size and coverage of mapped landslide inventories (Amatya et al., 2022).

Finally, the system does not consider the initial moisture content. Palau et al. (2023) studied the influence of including the initial soil moisture modelled by European Flood Awareness System (EFAS), obtaining empirical hydrometeorological thresholds. The results showed that these new thresholds improved the performance of this LEWS, especially in moderate and low susceptibility terrain.

3.4.3.8. How will GOBEYOND take this to the next level?

Scientific and technical progress in landslide susceptibility mapping faces certain impediments that need addressing. One area of improvement, highlighted by Nadim et al. (2006); Ciurleo et al. (2016); and Wilde et al. (2018), revolves around incorporating soil and geological datasets/maps, specifically the geotechnical properties of the soil, to enhance the overall quality of susceptibility maps. However, a noteworthy challenge in Catalonia is the absence of information on superficial formations within these maps (Palau et al., 2020).

Another critical aspect requiring attention is the refinement of current rainfall thresholds. The existing thresholds lack consideration for antecedent rainfall or soil moisture information, indicating a need for an updated approach to better capture the complex dynamics of landslide susceptibility (Palau et al., 2023).

While the documentation of landslide events in Catalonia has shown significant improvement, as indicated by Buxo et al. (2022), there is still opportunities for enhancement because of the abundance of aerial and satellite imagery, and the engagement of social networks. Integrating these resources can contribute to a more comprehensive and effective enhancement of landslide susceptibility mapping, aligning with the evolving landscape of available technologies and information dissemination channels.

In the pursuit of advancing landslide impact-based systems in Catalonia, **GOBEYOND** could play a pivotal role in the creation of a robust and impact-based forecasting system tailored to the region. Given that the development of such a system is iterative, it would require ongoing refinement and adaptation, considering insights from real-world examples and experiences.

Additionally, given the Catalan system's simplicity, this methodology could be applied to new or bigger domains.

4. Comparative analysis and perspectives of integration of relevant methodologies and technologies for geo and weather event real-time monitoring and impact-based early warning

In this section we compare the different proposed methodologies for real-time monitoring of weather and geo impact-based early warning systems. We discuss their integrability based on the appropriate time and spatial scale of concern, the level of readiness of the technology for operational and community-oriented uses, the actual end-users and the advantages and imitations of the near-operational and operational implementations of the methodologies.

4.1. Temporal scale

One big difference between weather and geo hazards is the timing of the early warning systems. The weather hazards have systems that provide information from months to minutes before an event, whereas the geo hazards provide information after an event has occurred (Table 3). For the geo hazards, the relevant issue concerns the time scale of application of the different considered hazards in relation to the difference between the expected time of the alert and the event origin time. The time of the alert depends on the time at which the event is detected by the monitoring network and the time needed to evaluate its source characteristics (location, magnitude, source spatial extent, source duration) and predict the potential impact. In some cases (e.g., earthquake early warning), the source and impact estimates can evolve with time, and become more and more refined and accurate as more stations and recorded signal time-windows are available for the alert.

The weather hazards however define early warning as the time needed to plan, prepare and take actions before an event happens. This is different depending on the hazards, but for most weather-driven hazards the EWS are able to provide signals days and even weeks ahead of an event. The information is usually uncertain for longer lead times but become more and more sharp as the event approaches. The use of ensemble forecasts has greatly improved the assessment of uncertainty and is a great tool when it comes to providing to improving decision making under uncertainty (Kumar & Murtugudde, 2013).

4.1.1. Temporal scales for Geo hazards

The table shows that all earthquake-related hazards (tectonic earthquakes, volcanic earthquakes, tsunami) are today capable of providing the expected impact within seconds (earthquake early warning) to tens of minutes (shake-map, run-up height map and loss estimation) after the earthquake origin time. However, the estimation of impact severity has a different level of accuracy, and it generally depends on the spatial density and coverage of the seismic network over the region of interest. The currently used early warning systems that predict the impact of ash fall after a volcanic eruption provide the alert that in some cases contains the information on the affected regions along with the predicted impact in terms of human/economical losses and building/infrastructure damage. As for landslide hazard, we note that the currently used early warning systems operate on rain-fall sensor networks deployed in the landslide-hazardous region, so that, in this specific case, the time of the alert generally precedes the event occurrence, and formally these methods are to be classified as “event forecast/prediction methods” depending on if the event occurrence and its impact are assessed in terms of probability of exceedance of thresholds set on theoretical or empirical bases, respectively.

Table 3 Temporal scale of warning times for weather and geo hazards

Hazard	Before the event				After the event		
	weeks	days	hours		seconds	minutes	hours
Flood early warning		1-15		Event			
Flash floods nowcasting **Flash floods early warning**			1-12 6-120				
Windstorms		1-15					
Storm surges		1-8					
Heat waves		1-15					
Drought onset and end	1-12						
Fire danger		1-15					
Earthquake Early Warning (EEW)					from 0 to 10-20		
Earthquake Rapid Response **Earthquake Loss Estimates**						2-3 20-30	
Volcano Early Warning (VEW) for ASH fall **Volcano Rapid Response (VRR)**						2-3	from 6 to 48
Tsunami Early Warning Systems						3-15	
Landslide Early Warning Systems			1-24				

Although all methodologies for early warning of geohazards work on automatic data processing workflows (that do not require human intervention), the deadline of data release varies from *real-time* (fractions of seconds with a certified deadline), *near-real time* (not certified deadline, spans over seconds to minute) and *off-line* (data are available only after the event end). While Earthquake Early Warning systems are *real-time* systems, rapid-response systems (earthquake shake map, loss estimate, volcanic ash fall impact, tsunami) can be classified as near-real-time or offline depending on the time all data used for the alert are available. The need for a rigid and very short deadline for earthquake early warning systems is justified by the fast propagation of damaging waves after the event occurrence. Since the landslide monitoring is not performed during the event occurrence, this classification does not apply to this specific geohazard.

4.1.2. Temporal scales for Weather hazards

For the weather hazards, most-weather related hazards (floods, windstorms, storm surges, heat waves and fire risk) share the forecast horizon of up to 15 days. The skill of the forecast declines quite quickly with lead time and is also very depending on the variable, the current weather situation and location. It is therefore very difficult to provide a general rule of how to label the predictability of a forecast. It also depends on how predictability should be interpreted and what the end user finds a valuable forecast.

The general skill of the forecast is continuously improving over time (Bauer et al., 2015). The general trend over the past years have been improvement with one day per decade, which should be interpreted as "a 1 week forecast today is as good as a 4-day forecast 30 years ago"

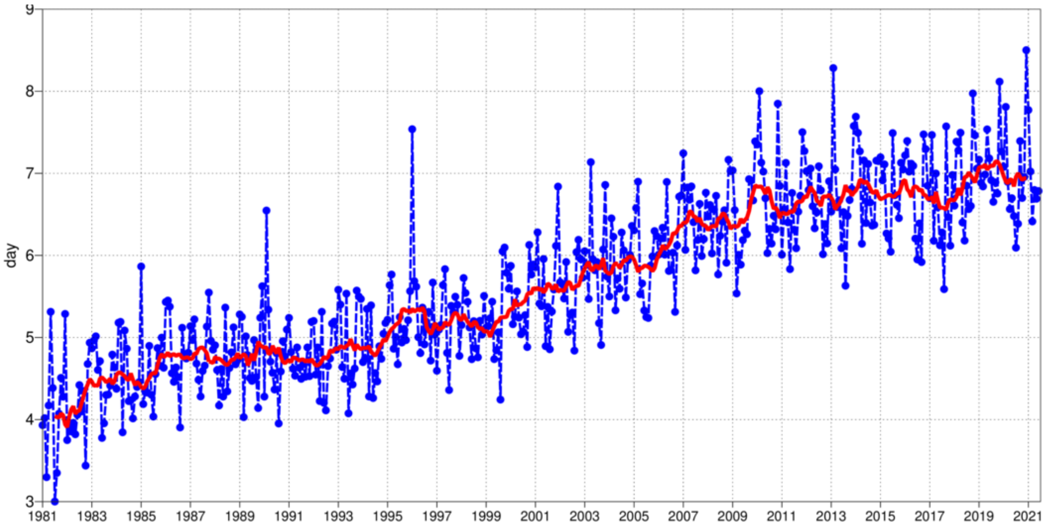


Figure 36. Primary headline score for the high-resolution forecasts.
Evolution with time of the 500 hPa geopotential height forecast performance – each point on the curves is the forecast range at which the monthly mean (blue lines) or 12-month mean centred on that month (red line) of the forecast anomaly correlation (ACC) with the verifying analysis falls below 80% for Europe. Source: Haiden et al, 2022.

Recent developments using AI for weather forecasting has in a very short time span increased the speed at which forecasts are improving. The new ML models for weather variables are on par and even surpassing the current NWP in terms of skill. Since this is a very new application of LM models, it is too early to say when the improvement capacity is reached. Fire danger hazard is different from the other weather hazards as it requires ignition for fire to actually happen, and it is only very recently with AI models that we are able to correctly predict the actual occurrence of forest fires (McNorton & Di Giuseppe, 2024). The last few years has seen rapid development of forecast skill thanks to machine learning, and it is difficult to say how this will affect the forecasting of weather in the coming years.

4.2. Spatial scale

The spatial scale (Table 4) over which the geo alert is effective for each considered hazard determines the lead-time, e.g., the time available for safety emergency actions before the event impact but also the extent of the region where the warning is effective in predicting the severity of the event impact in terms of human losses, injuries, building damage and economical losses. For the weather hazards, the spatial scale denotes the area over which it operates. The spatial extent of individual hazards depends on the scale of the phenomena.

4.2.1. Spatial scales for Geo hazards

Except for earthquake early warning, all explored methodologies for geohazard early warning cover a region where the alert is effective in an area spanning from the local (10 km radius around the source), to regional (100 km radius around the source) and national (500-1000 km radius around the source) scale. This area is roughly estimated considering the extent of the significant impact region, which critically depends on the source magnitude/intensity. Nation-wide EEWS are operated by the main seismic agency in several countries (Japan, Mexico, California, Romania, South Korea) and the alert is disseminated to local/national authorities or in the case of Japan and Mexico to the large public, even using cellular app technologies. In many other countries worldwide, EEWS are under development or implemented at a prototype stage for testing and validation. In Italy, the first EWS for high-speed railways is under construction and testing on a limited segment of the national railway network, linking the cities of Naples and Rome, in the framework of a joint academic/industrial partnership.

Onsite early warning systems are effective at the km-scale, and useful to protect localized targets as industrial plants, hospitals, schools. The main advantage of onsite vs local/regional (or network-based) source-based, EEW systems is the generally faster alert and more reliable impact prediction based on the measurement of the P-wave ground motion amplitude at the site to be protected. On the other hand, source-based local and regional systems grounds on region-specific empirical attenuation relationships to predict the peak ground shaking based on the event distance and magnitude. In **GOBEYOND** we propose a new methodology that combines source- and impact-based approaches to infer the event strong-shaking zone, that uses the early P-wave information.

All rapid response and loss estimation techniques apply to regions encompassing the local, regional and national scale. Data for computing shake-maps are generally available within 30 minutes from the earthquake occurrence depending on the data-transmission technology that is used to streaming the recorded acceleration waveforms or the peak motion estimations at the strong motion sites to the central data server for the map elaboration. The shake map accuracy is critical dependent on the spatial density and coverage of the strong motion network and on the accuracy of the adopted ground motion prediction model. The appropriate correction for site amplification effects is also a limiting factor for obtaining reliable prediction of the ground motion intensity in the region of concern. The use of 1D (epicentral distance-dependent) attenuation relations and approximated methods to account for site effects (soil category classification, topography amplification factors, spatial correlation) in shake-map calculations make the impact estimation affected by relatively large uncertainties at not instrumented sites.

Table 4 Spatial scale of weather and geo hazards

	Onsite (1km)	Local (10-20km)	Regional (50-100km)	National (200-1000 km)	Trans-national (>1000 km)
Flood early warning systems					
Flash floods warnings					
Windstorms					
Storm surges					
Heat waves					
Droughts					
Fire danger					
Earthquake Early Warning (EEW)					
Source-based impact estimates				*	
P-wave based impact estimates					
OnSite Alert Level					
Onsite P-wave based					
Earthquake Rapid Response and Loss Estimates					
USGS services - ShakeMap, ShakeCast and PAGER				**	
SIGE - Information System for Emergency Management in Italy					
SEISAid-Antilles tool: rapid response in French West Indies					
Bayesian updating of loss estimates					
ELER system - Earthquake Loss Estimation Routine for Turkey					
QLARM					
Volcano Early Warning (VEW) + Volcano Rapid Response (VRR)					
EASE					
Volcanic Ash EWS					
Volcanic Ash Rapid Response (VRR)					
Tsunami Early Warning Systems					
ICG/NEAMTWS - North-eastern Atlantic, the Mediterranean					
CENALT					
CAT - Tsunami warning in Italy					
VOlcano Notice for tsunami Threat (VONUT)	***				
Landslide Early Warning Systems					
The Norwegian LEWS					
The Italian (Tuscany) LEWS					
The Catalan LEWS					

* Selected users outside of the academic group
** There are countries (Japan, Mexico, Romani, California, South Korea) in which the alert is distributed to users at different scales
*** Local alert for landslides triggered by volcanoes
**** EFAS information is restricted to only partners

Loss estimation methods combine the shake-map output with the vulnerability assessment. In addition to the commonly used technique developed by USGS (Shakemap@USGS), in **GOBEYOND** the method QLARM is also proposed to calculate losses, based on intensities (accelerations) using the shortest distance to a line source modelling the rupture, based on the rapid estimations of the source magnitude and location. Global population databases provide the amount of people exposed to a given ground-shaking and potential damage level, leading to a gross estimation of potential casualties and economic losses whose accuracy critically depend on country-specific vulnerability and loss models.

Tsunami early warning systems span the trans-national spatial scale (1000+ km radius), with the goodness of the impact estimation that strongly depends on the accuracy of the source parameter estimates (magnitude, depth) and modelling accuracy of the tsunami wave propagation through irregular sea bottom bathymetry and coastal areas.

Up-to-date volcano early warning systems monitor and analyse the risk consequent to eruption precursory phenomena (mainly earthquakes) and post-event ash dispersion and fall on medium to long distance ranges.

Landslide hazard can affect the onsite, local, and regional scale, the latter in specific geomorphological conditions associated with wide irregular topography areas susceptible to experience a landslide due to various triggers can vary depending on the local climate conditions, geological settings, and other environmental factors. Landslides early warning systems ground on regional rainfall monitoring networks that assess the potential of landslide triggering based on rain level threshold exceedance criteria.

4.2.2. Spatial scales for Weather hazards

The spatial scales on where the weather impact models operate are quite different from their maximum spatial coverage. For example, the EFAS system covers the entire continent on Europe, but still provides information on the fine scale (a few km) in terms of where events happen. However, in terms of fluvial floods they are usually quite large and can cover entire river basins. For flash and urban floods, the scales are much smaller and are focussing on localised events. However, the actual warning can be given to cover a larger area since the likelihood of an event comes with a spatial uncertainty.

Windstorms and heat waves typically affect larger regions and do not have the only local effect. For these events to trigger, there needs to be a large-scale driver such as a major storm or a long-persisting blocking causing a heatwave. Smaller scale phenomena such as Medicanes can still affect a rather small region but is till never considered to be local.

Drought and wildfires usually cover quite a large region, with variability that is dependent on the location. For example, a large region can be under drought-like conditions, but the impact is heavily dependent on the resilience and potential to cope with adverse effects. Wildfire danger indices like FWI are purely weather-driven and will usually also affect a larger region. However, using only FWI is not really providing a full picture of the risk since it does not take for example available fuel into account.

4.3. Technological maturity

The currently proposed Geo and weather hazard impact-based EW methods show a heterogeneous level of technological maturity, robustness, and reliability of the impact prediction. Some of them does not have a mature system for operational use in support to emergency management operation. This is specifically the case of earthquake early warning systems whose time- and spatial-scale of applications generally requires extremely fast individual or automatic actions, that can be taken based on an uncertain and poorly verified alert.

Without claiming to want to provide an exhaustive evaluation of the level of technological maturity of the different illustrated methodologies of impact-bases EW, we propose to rank them according to the scale proposed by the European Commission for assessing the degree of maturity of a technological product with application for the society.

4.3.1. Technical maturity for Geo hazards

Table 5 shows the TRL for each of the proposed methodologies. Overall, the technology for volcano, tsunami and landslide hazards has reached a higher maturity level, with most of the proposed methodologies already being implemented into operational platforms. Similarly, for the Earthquake Rapid Response (ERR) there are methodologies already embedded into existing platforms, that can provide impact estimates in fully automated way. Different is the case of EEW, for which all the methodologies are experimented and tested offline, but none of them (among those cited in the list) is currently implemented into operational systems. The lack of a local/national plan for the management of real time earthquake alerts, the lack of a clear regularization in terms of responsibilities for incorrect/missed warnings and the lack of a dedicated campaign for the education of the population are among the elements that currently limit the development of EEWS.

In the case of existing platforms for ERR, the knowledge of the exposure and vulnerability of buildings at the scale of the affected area is a crucial issue. Recent research efforts have established exposure models for buildings across Europe (Crowley et al., 2021), where building types are classified based on the GEM Building Taxonomy v3.1 (Silva et al., 2022). When more refined analyses are required in a local context, specific approaches need to be implemented, such as the exploitation of national statistics databases or the collection of representative data from field inventories (Fayjaloun et al., 2021). A specificity of earthquakes pertains to the consideration of aftershock risk: while there are several models that account for the effect of cumulated damage (e.g., state-dependent fragility models), only very recent studies have considered the risk assessment of cumulated damage under repeated shocks in a rapid post-earthquake context (Nievas et al., 2025). Another type of induced effects by earthquakes is the disruption of road transportation network, especially due to the obstruction by debris from damaged or collapsed buildings. Again, several research studies have worked on this aspect (e.g., Argyroudis et al., 2015), including the prioritisation of emergency relief itineraries (Gehl et al., 2022); however, the operationalisation of such research outputs into ERR platforms is not ready yet.

A common aspect for some methodologies related to different geo-hazards is that, although the methodology is implemented into some operational platform, there is no posterior validation of the outputs in terms of successful and unsuccessful (false, missed) alerts. Moreover, there is no planned timeline for periodic method performance assessment and upgrading. For this reason, we have been rather conservative in attributing the TRL, also for methodologies that are stated or generally believed to be operational.

4.3.2. Technical maturity for Weather hazards

The weather hazard and impact models are generally on a very high TRL with years of operational use. Exceptions from this are storm surges and heat waves, where local systems are used in operations with some examples, such as the UK National tide gauge network for storm surges, and the MeteoSwiss system for heat waves. However, neither of these hazards have a European-wide warning system although some prototypes for these systems exist, for example the ANYWHERE platform for storm surges.

For wind storms the operational capacity for the hazard is high, but there is no system which is issuing specific impact-based warnings. This is mainly due to the nature of the hazard, since the impact can be of very different kinds ranging from falling trees, blown-off roof-tops to fires and flooding caused by waves and damaged electrical system. The question is then whether an impact-based warning makes sense for windstorms since the effects can be so diverse.

4.4. End users

The piece of information about the TRL is also closely linked to Table 6, describing the current end-users that benefit from prediction (or outcomes) of the methodologies. Generally, the methodologies which have a higher TRL are also those which already distribute the expected outcomes to local authorities and CP, both at regional and at national scale, depending on the considered hazard. A few of the proposed methodologies already disseminate the warnings to the public, while others are still limited to academic users (this is the case of EEW methods).

4.4.1. End users for Geo hazards

In Table 6 we show that for almost all approaches, except for earthquake early warning, the warning message is issued to decision-makers and emergency managers (local authorities, civil protection) while a limited number of the described methods interface directly with public. This is the case for tsunami warning that can be lifesaving if issued to the population living along coastal zones at risk. In some EU countries, such as Italy, the management of emergency related to the occurrence of natural hazards and related communication, that includes the possible alerts, is in charge of the national Department of Civil Protection, that uses data and consulting from Competence Centers and Regional Civil protection Offices located in the most hazardous areas of the Italian territory.

4.4.2. End users for Weather hazards

The end user groups for weather hazards depend on the hazard but in general the picture is similar as for the geo hazards. The Hazards with an established system and a high TRL also have the already established end user group. In principle, all systems are of interest for academic research, but in some cases the systems themselves are mostly technical and therefore does not have a strong scientific interest. All CEMS systems are also directly reporting to the Emergency Response Coordination Centre (ERCC) Some systems, such as EFAS, has per definition a user group which is very clearly identified because the information is not publicly available, instead it is provide to expert users. For floods, the public will instead rely on information from local bodies.

Table 5 Technical readiness level (TRL) for the systems described in this report.

System	TRL
Flood forecast early warning system	
National hydromet services (ex FFC, SMHI)	9
Continental-scale systems (EFAS)	9
Flash floods	
Local flash flood systems	6-9
European (EPIC)	9*
Windstorms	
MeteoSwiss demonstrator	6
NHMS systems (e.g., SMHI)	9**
Storm surges	
National systems (e.g., Netherlands, UK)	9
Anywhere platform	5
Heat waves	
Local forecasts (Swiss system)	9
European-wide systems	5
Droughts	
Local drought forecasting systems (E.g., Catalan drought viewer)	8
Large-scale systems (EDO)	9
Fire danger	
National warning systems (e.g., SMHI)	9**
European-scale system (EFFIS)	9**
Earthquake Early Warning (EEW)	
Source-based impact estimates	5
P-wave based impact estimates	4
OnSite Alert Level	5
Onsite P-wave based	4
Earthquake Rapid Response and Loss Estimates	
USGS services - ShakeMap, ShakeCast and PAGER	6-9*
SIGE - Information System for Emergency Management in Italy	6-9*
SEISAid-Antilles tool: rapid response in French West Indies	6-9
Bayesian updating of loss estimates	3
ELER system - Earthquake Loss Estimation Routine for Turkey	6-9
QLARM - Quake Loss Assessment, Response, Mitigation	6-9
Volcano Early Warning (VEW) + Volcano Rapid Response (VRR)	
EASE	6-7
Volcanic Ash EWS	6-9*
Volcanic Ash Rapid Response (VRR)	6-9*
Tsunami Early Warning Systems	
ICG/NEAMTWS - North-eastern Atlantic, the Mediterranean	6-9*
The CENALT - The Cenalt, the French Tsunami Warning Centre	6-9*
CAT - Tsunami warning in Italy	6-9*
VOlcano Notice for tsunami Threat (VONUT)	4
Landslide Early Warning Systems	
The Norwegian LEWS	6-9*
The Italian (Tuscany) LEWS	6-9*
The Catalan LEWS	3

* Methodology and technology operational but there are no posterior performance analysis or validation
** System for hazard warning exists, however not providing impact forecasts

Table 6 End user groups for the hazards

	Academic	General public	Private infrastructure manager	Local authorities and civil protection	National Civil protection
Flood early warning					
National hydromet services (ex FFC, SMHI)					
Continental-scale systems (EFAS)**					
Flash floods					
Local flash flood systems					
European (EPIC)					
Windstorms					
MeteoSwiss system					
NHMS systems (e.g., SMHI)					
Storm surges					
National systems (e.g., Netherlands, UK)					
Anywhere platform					
Heat waves					
Local forecasts (Swiss system)					
European-wide systems					
Droughts					
Local forecasting systems					
Large-scale systems (EDO)					
Fire danger					
National warning systems (e.g., SMHI)					
European-scale system (EFFIS)					
Earthquake Early Warning (EEW)					
Source-based impact estimates	*	*	*	*	*
P-wave based impact estimates	*				
OnSite Alert Level	*				
Onsite P-wave based	*				
Earthquake Rapid Response and Loss Estimates					
USGS services					
SIGE					
Bayesian updating of loss estimates					
SEISAid-Antilles tool					
ELER system -					
QLARM					
Volcano Early Warning (VEW) + Volcano Rapid Response (VRR)					
EASE					
Volcanic Ash EWS					
Volcanic Ash Rapid Response (VRR)					
Tsunami Early Warning Systems					
ICG/NEAMTWS				not sure	not sure
CENALT					
CAT (Italy)					
VONUT					
Landslide Early Warning Systems					

	Academic	General public	Private infrastructure manager	Local authorities and civil protection	National Civil protection
The Norwegian LEWS				not sure	not sure
The Tuscan LEWS					
The Catalan LEWS					

* Selected users outside of the academic group
** EFAS information is restricted to only partners

4.5. Pros, cons and common features

We finally summarize the advantages and limitations of the proposed impact-based methodologies according to their scientific grounds, data availability, technological implementation, and level and robustness of validation. We identify the pros and cons of all considered methods, by classifying them into broad macro-categories, related to:

Data, e.g., the availability of dense monitoring network, the distribution and coverage of the available networks, the quality of monitoring data, the availability of different types of observations.

Methodology, e.g., the robustness and limitations of the proposed approach, the accuracy of impact predictions, the assessment of uncertainty on predictions.

Technology, e.g., the technological requirements needed to implement the methodology, the need of a dedicated telecommunication infrastructure, the necessity of real-time streaming of data, the availability of operational software.

Application and validation, e.g., the integrability of the methodology into existing platforms, the release of output to end-users, the communication of hazard predictions.

4.5.1. Pros and cons for Geo hazards

Overall, most of the pros and cons of the methods for geo-hazard are related to methodological aspects. Robustness, quickness, and simplicity of the approaches are common, positive features among different methods. A critical aspect is often related to the lack of uncertainties on predictions (or poor uncertainty evaluation) and to the non-adequate modelling of exposure and vulnerability (e.g., for volcanic risk).

The availability of good quality and dense observations constitutes a weakness for those hazards (and the related methodologies) which operate on a short time scale (such as earthquake early warning and tsunami hazard). Technology turned out to be a critical issue only for earthquake early warning, for which the availability of real-time data is a fundamental requirement. Finally, the major limitations in terms of application/validation of the proposed methodologies are related to the communication of hazard estimates to the non-expert audience.

4.5.2. Pros and cons for Weather hazards

The pros of the weather hazards are the well-established methods for calculating the risks in terms of the hazards themselves. Since most of them rely on weather forecasts in terms of numerical weather predictions, the systems are well-established with a robust technical infrastructure to deliver forecasts. Dissemination platforms are well-known and are constantly co-evolving with the users. Uncertainty estimation through for example ensemble forecasting is now the norm, which hugely has improved the skill of the forecasts.

The disadvantages are also related to data. Often the lack of reliable data makes good calibration and bias correction of the forecasts suboptimal and difficult. This can lead to misses and false alarms which undermine the public trust in forecasts. The forecasts generally underestimate extreme events. The reason for this can be that the scales at which forecasts cannot correctly represent the processes that lead to extreme events, or that uncertainty in the forecasts lead to missed events.

New technology, such as better remote sensing data and machine learning techniques offer great potential in improving the systems, which means that the skill of the forecasts is improving, and there is potential for development.

4.6. Integrability of Geo and Weather EW methods in a unique platform

The biggest challenge in integration of weather and geo hazards comes from the difference in the temporal scale. Geo hazards have systems that are reacting to events that are occurring in real-time, whereas weather hazards usually anticipate the events with long lead times. Therefore, the technical design of the systems is quite different. Also, the dissemination will be a challenge, geo hazards rely on fast and simple alert systems to put people into safety as quick as possible, whereas weather warnings are detailed information that provides time to act on the risks before they have a big impact.

However, the underlying data vulnerability and exposure data will in many cases be similar, so there is a scope for harmonising this data to create synergies in the risk assessment. Further, the combined risks are very interesting in terms of increasing impact. For example, during extreme weather events the civil society might already be stretched in terms of resources and make it more vulnerable if other hazards would occur at the same time, and vice versa. Therefore, a combined risk system would have merit for decision makers and civil protection agencies in terms of deciding the best course of action in each situation.

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Appendix A. Storm surge models and examples of early warning systems

A.1. Storm surge models

A.1.1. SELFE - A Circulation Model for Oceans and Estuaries

SELFE is an open-source toolkit, designed for the effective simulation of 3D baroclinic circulation. It utilizes unstructured triangular grids and was originally developed to address modelling challenges in the Columbia River estuary and plume. SELFE has been applied to study circulation in coastal margins worldwide. The model employs a semi-implicit finite-element/volume Eulerian-Lagrangian algorithm to solve the Navier-Stokes equations, capable of handling both hydrostatic and non-hydrostatic forms. SELFE's numerical algorithm is characterized by high-order accuracy, robustness, stability, and computational efficiency. Additionally, it incorporates wetting and drying of tidal flats (Y. Zhang & Baptista, 2008).

A.1.2. SLOSH model – A model for the Sea, Lake, and Overland Surges from Hurricanes

The SLOSH model, developed by the National Weather Service (NWS) (Jelesnianski et al., 1992) remains the operational model utilized by the National Hurricane Center due to its computational efficiency. This model divides the coastline into 32 basins, covering the entire US Atlantic and Gulf of Mexico coastlines. These basins are strategically centered on vulnerable features such as inlets, populous coastal areas, low-lying terrain, and ports. Each basin is represented by a detailed mesh or grid, capable of resolving ocean bathymetry and land features with precision, although it does not extend into the open ocean.

A.1.3. SCHISM model

The SCHISM modelling system (Y. J. Zhang et al., 2016) is derived from the SELFE model and is an open-source, community-supported modelling system based on unstructured grids. It is designed to seamlessly simulate 3D baroclinic circulation across various scales, including creek-lake-river-estuary-shelf-ocean. Utilizing a highly efficient and accurate semi-implicit finite-element/finite-volume method with a Eulerian-Lagrangian algorithm, SCHISM solves the Navier-Stokes equations (in hydrostatic form) to address a wide range of physical and biological processes. The numerical algorithm combines higher-order with lower-order methods to achieve stable and precise results efficiently. Mass conservation is enforced using the finite-volume transport algorithm, and the model naturally incorporates wetting and drying of tidal flats.

A.1.4. Bayesian Hierarchical model

Bayesian hierarchical models (BHMs) present an alternative statistical approach that leverages tide gauge observations and geospatial statistics to estimate extreme return levels with reduced uncertainty. A recent study (Boumis et al., 2023) focuses on applying a BHM to estimate extreme storm surge frequency along the US Gulf Coast, where hurricane-generated storm surges are common. The BHM aims to provide more accurate estimates and interpolate information to ungauged coastal areas, ultimately aiding in comprehensive coastal flood risk management.

A.2. Examples of early warning systems for storm surges

A.1.5. Early-Warning System for storm surge and tide in Mauritius

Mauritius, a small island in the Indian Ocean, has implemented its own early warning system for storm surge and tide in collaboration with Deltares and the Ministry of Environment, Sustainable Development, Disaster, and Beach Management. This system predicts and alerts coastal communities about impending storm surges, aiding timely evacuations during cyclones. In addition, it enables timely and safe evacuation of coastal areas in Mauritius, Rodrigues, and Agalega Islands during extreme water levels. The system runs five 2DH Delft3D hydrodynamic models every six hours, with a three-day forecast horizon, simulating coastal water levels. Operational management is facilitated through Delft-FEWS, incorporating real-time data from Automatic Weather Stations and blending cyclone track bulletin information with numerical weather predictions. This nation-wide forecasting system, installed at the Mauritius Meteorological Service, generates three-day forecasts every six hours based on the latest weather forecasts and tropical cyclone bulletins, enhancing resilience and preparedness against storm surges and tides (Bogaard et al., 2016).

A.1.6. European storm surge model

The European Storm Surge model was developed and validated during the ANYWHERE Project to provide pan-European storm surge forecasts. It integrates storm surge, tidal, and wave models, showing satisfactory predictive performance with various atmospheric forcing datasets. Validation results demonstrated good predictive skill. Coupling with tides and increasing atmospheric forcing resolution enhanced predictive accuracy, particularly in shallow areas. A hindcast dataset (ANYEU-SSL) covering 40 years of Storm Surge Levels (SSL) data along the European coastline showed an average RMSE of 0.10 m compared to tidal gauge data and 0.07 m compared to satellite altimetry data. The model accurately reproduced significant wave height (SWH), with RMSE lower than 0.5 m for over 50% of buoys and %RMSE below 10% for satellite measurements. Coupling waves, tide, and surge improved predictions for both storm surge level and significant wave height. Utilizing scatterometer wind data from satellite measurements for statistical corrections, bias correction techniques enhanced SSL and SWH predictions, particularly in extreme events and semi-enclosed areas like the Baltic and Mediterranean Seas. The analysis of the steric effect highlighted its contribution to extreme water levels, underscoring the importance of incorporating this process into modelling algorithms for more precise predictions (Fernández-Montblanc et al., 2020; Vousdoukas et al., 2020).

A.1.7. Regional storm surge model

A regional storm surge model for storm surge forecasting at regional scale has been applied to pilot sites in Europe. It is based on the regional scale circulation model (SCHISM) and the regional scale wave model. Exemplarily, the performance of the regional storm surge model was assessed through validation against historic events, focusing on extreme events exceeding a 5-year return period at the Stavanger tidal gauge. The model demonstrated satisfactory performance in reproducing total water levels, with absolute errors of maximum total water levels during extreme events ranging between 0.05 and 0.1 m. However, the results revealed an underestimation of maximum water levels, with larger uncertainty associated with the tidal component of the total water level (ANYWHERE, 2019).

A.1.8. Global hindcast model of storm surges

A hindcast is a simulation of past weather or ocean conditions, used to validate models by comparing simulated outputs to observed data. Hindcasts can also be valuable for understanding historical events or long-term trends in weather or ocean behaviour. A promising recent study (Mentaschi et al., 2023) presents a global hindcast of waves and storm surges using an unstructured mesh with unprecedented resolution, developed over a 50-year period. Utilizing the SCHISM circulation model coupled with the WWM-V (WindWaveModel) and forced by ERA5 reanalysis data, the model achieves good skill in reproducing sea surface height (SSH) and Significant Wave Height (Hs), with improved nearshore dynamics compared to previous lower-resolution studies. The dataset, validated against observations from satellite altimeters, tidal gauges, and buoys, provides a comprehensive set of wave-related fields with a 3-hour time step, offering potential for more accurate global-scale assessments of coastal hazard and risk.