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Review

# Operational early warning systems for water-related hazards in Europe

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ABSTRACT

Preparedness towards natural hazards is a key factor in the reduction of their impact on the society. Recent international initiatives are fostering the development of a culture of risk prevention and the promotion of early warning systems. Numerical weather predictions have become the basis of several flood-related warning systems, enabling the detection of hazardous events with sufficient lead-time to prepare effective emergency and response plans. The objective of this paper is to review current European operational warning systems for water-related hazards induced by severe weather conditions. In details, it includes systems for detecting surface water flooding, flash floods, debris flows, mud flows, rainfall-induced landslides, river floods and coastal floods. Technical features and capabilities of different systems are described, together with some noteworthy examples. The main strengths of each system type are highlighted and suggestions are provided for developing and further improving their overall skills in hazard detection and the mutual coordination.



## 1. Introduction

An increasing number of disasters caused by natural hazards throughout Europe have been recorded in the past decades, affecting millions (Fig. 1; CRED, 2011; European Environment Agency, 2010) and causing an increase in economic losses (e.g., Barredo, 2009). The increase in losses up to now has mostly been associated with societal changes, rather than human-induced climatic changes (Barredo, 2009). Yet, it can be expected that extreme weather events, causing most of the natural disasters, will increase with changing climate (Easterling et al., 2000; Morss et al., 2011). Rising human and economic impacts of natural hazards have triggered the European Commission to develop legal frameworks such as the Water Framework Directive 2000/60/EC (2000) and the Floods Directive 2007/60/EC (2007), to increase prevention, preparedness, protection and response to such events and to promote research and acceptance of risk prevention measures within the society. An important part of a holistic approach to risk management of natural hazards is the set up of early warning systems. Early warning can be defined as 'the provision of timely and effective information, through identified institutions, that allows individuals exposed to a hazard to take action to avoid or reduce their risk and prepare for effective response' (ISDR, 2004). Recent studies have illustrated that early warning systems can have significant benefits exceeding their development and maintenance cost (e.g., Rogers and Tsirkunov, 2011; Teisberg and Weiher, 2009).

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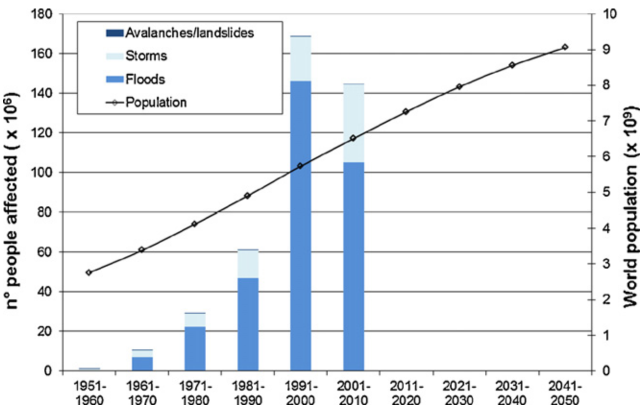



**Fig. 1 – Global water-related disasters in the world in the last 60 years. Mean yearly number of people affected per decade (stacked bars) and comparison with global population, including trend for the future 40 years. *Sources*: CRED (2011); U.S. Census Bureau, Population Division (2011).**

The aim of this review is to raise the awareness towards the capabilities of early warning systems for water-related natural hazards and, at the same time, contribute to the development of a culture of risk prevention rather then relying on post-disaster response and recovery. For this purpose, we present characteristic examples and innovative approaches of operational early warning systems in Europe for water-related natural hazards. The adjective ''early'' is here meant to identify those events that can be detected before the causative phenomenon occurs and any damage takes place. For example, cyclonic air masses producing floods in large river basins are nowadays skillfully predicted by current numerical weather predictions (NWP) some days in advance. On the other hand, hazards like tsunamis produced by severe earthquakes or sudden dam failures are detected only after their onset and no real ''early'' warning can be issued. For water-related hazards, the use of accurate forecasts of the atmospheric state is therefore a key point, as they largely influence the overall system performance. Current NWP have become the basic input to these systems, enabling the detection of hazardous events with sufficient lead-time for preparing effective emergency and response plans. The key role of NWP-based systems is that their skill is directly linked to advances in the input weather predictions, therefore increasing the forecast horizon can lead to significant risk reduction.

In the selection of warning systems to include in this overview, particular emphasis is given to those (1) running operationally and (2) issuing warning, in case hazardous conditions are detected, either to the public or to emergency units. Most of the reported systems operate at national or regional level, though some noteworthy super-national initiatives are pointed out. The presented collection is mostly based on published documents, such as journal articles, books, conference proceedings, as well as websites. The authors are aware of a number of additional operational systems where little or no information on their warning procedures is publicly distributed.

Section 1.1 describes the main political and legal drivers for the development of early warning systems as important part of a risk prevention strategy. In Section 2 the main water-related natural hazards in Europe caused by atmospheric forcing are illustrated and different characteristics of the specific operational early warning systems are presented, including some prominent examples. Section 3 outlines and discusses the current difficulties related to the different early warning systems, their common aspects and differences, future trends and challenges. Finally, a summary of the findings of this paper is presented in Section 4.

### 1.1. *Political and legal drivers for the increased development and use of early warning systems*

A great diversity of legal frameworks for risk management and reduction of natural hazards exists within the Member States of the European Union. Whereas countries or even administrative regions, which have frequently been exposed to natural hazards, often have well developed management plans and the institutional capacity to reduce and remediate the impact of natural hazards, others are just at preliminary stages of building up their response capacity. Early warning systems are essential features of Civil Protections and are commonly recognized as vital risk prevention tools (European Commission DG Environment, 2008). Thus, alongside with raising the awareness that an integrated approach should be used in response to disasters, early warning systems are usually nowadays embedded in the integrated disaster cycle (e.g., European Commission, 2009). Case studies have shown that the national policy framework for such an integrated disaster management mainly originates from external policy requirements such as European Commission directives and/or international initiatives (European Commission DG Environment, 2008). Those external policy requirements are in turn often in response to global climate change or large scale natural disasters as is the case of the Flood Directive (FD, European Commission, 2007). Following the major floodings that occurred in Europe in the last decades, the European Commission promoted the compilation of a new directive for flood prevention and mitigation to achieve a uniform level of protection for all citizens of the European Union. The FD prompted Member States to review their current flood risk management in a three-step approach, to be coordinated with the Water Framework Directive (WFD, European Commission, 2000) implementation cycle. The FD is focused on all kinds of floods, including river, lakes, flash floods, urban floods, coastal floods, storm surges and tsunamis. It requires Member States to assess if rivers and coasts are at risk and to take adequate and coordinated measures to reduce this risk. According to European Commission (2004), flood risk management incorporates the following elements:

1. *Prevention*: preventing damage caused by floods by avoiding construction of houses and industries in present and future flood-prone areas; by adapting future developments to the risk of flooding; by promoting appropriate land-use, agricultural and forestry practices;
2. *Protection*: taking measures, both structural and non-structural, to reduce the likelihood of floods and/or the impact of floods in a specific location;

**Table 1 – Quantitative precipitation forecast products and technical details.**

| Product type | Spatial extent | Resolution | | Forecast range | References |
|---|---|---|---|---|---|
| | | Spatial | Temporal | | |
| Radar nowcasting | ~10 000–50 000 km$^2$ | 1–4 km | 5–60 min | 1–6 h | Seed (2003); Turner et al. (2004); Berenguer et al. (2005) |
| Ensemble radar nowcasting | ~10 000–50 000 km$^2$ | 1–4 km | 5–60 min | 1–6 h | Germann et al. (2009); Panziera et al. (2011) |
| Radar-NWP blending | Regional | ~2 km | 15–60 min | ~6 h | Golding (1998); Bowler et al. (2006); Atencia et al. (2010) |
| Limited area NWP | Regional–continental | 2–25 km | 1–6 h | 1–3 days | Rotach et al. (2009) and references therein |
| Ensemble limited-area NWP | Regional–continental | 4–25 km | 3–6 h | 1–5 days | Rotach et al. (2009) and references therein; TIGGE-LAM project (http://www.smr.arpa.emr.it/tiggelam/) |
| Global NWP | Global | ~15–100 km | ~3–6 h | ~5–30 days | Buizza et al. (2005); Bougeault et al. (2010) |
| Seasonal forecasts | Global | ~15–100 km | ~6–24 h | Months | Palmer et al. (2004) and references therein |

3. *Preparedness*: informing the population about flood risks and what to do in the event of a flood;
4. *Emergency response*: developing emergency response plans in the case of a flood;
5. *Recovery and lessons learned*: returning to normal conditions as soon as possible and mitigating both the social and economic impacts on the affected population.

Early warning systems (EWS) are specifically mentioned in the FD as an essential part of an effective preparedness towards natural disasters. As a result of the implementation of the FD, Member States put an increased effort to either improve their existing EWS or, if no system existed previously, to develop new ones.

A broader international political approach to promote early warning systems as an important tool for risk reduction of natural hazards is the Hyogo Framework for Action (United Nations, 2005). The framework was adopted at the United Nations World Conference on Disaster Reduction and emphasizes the need for building the resilience of society to disasters. It provides guidance on how to reduce disaster risk and its impact. Similarly to the FD, early warning systems are also endorsed as an essential investment that protects lives and property, thus contributing to a sustainable development. Furthermore, it stresses the cost-effectiveness of EWS in coping mechanisms towards the mere reliance on post-disaster response and recovery (United Nations, 2005). To further promote the development and use of EWS, the International Strategy for Disaster Reduction of the United Nations (UN-ISDR) set up a Platform for the Promotion of Early Warning (PPEW) which identifies four elements to constitute an early warning system (Basher et al., 2006): (i) risk knowledge, (ii) monitoring and warning service, (iii) dissemination and communication and (iv) response capability. In this article we will mainly focus on point (ii) of the ISDR classification, which concerns the technical and scientific details of warning systems, while point (iii) will be discussed in Section 3.

## 2. Operational early warning systems in Europe

Natural hazards occur at different scales in space and time. As a result, systems for monitoring and forecasting extreme events have so far been developed and tailored to the scale of interest of the phenomenon to foresee. Yet, early warning systems for water-related hazards make use of several types of meteorological input data, covering a wide range of space and time scales, often overlapping among different systems. Fig. 2(top panel) compares the event magnitude with the onset time and duration after the triggering phenomenon, for the considered systems. Corresponding state-of-the-art meteorological input data for monitoring and forecasting these hazards are shown in the bottom panel, with a qualitative picture of their skill towards the forecast lead time. Quantitative information on the main available products used as meteorological input for operational EWS is shown in Table 1, together with references to some key examples. In the following, each system type is described, according to the proposed order of time scales involved.

### 2.1. Rainfall-induced landslides, mud flows and debris flows

Intense or prolonged precipitation is the main trigger for debris flows, mudflows and landslides (e.g., see Fig. 3). In 2007, precipitation was the responsible trigger for roughly 90% of worldwide casualties due to landslides (Petley, 2008). The basis

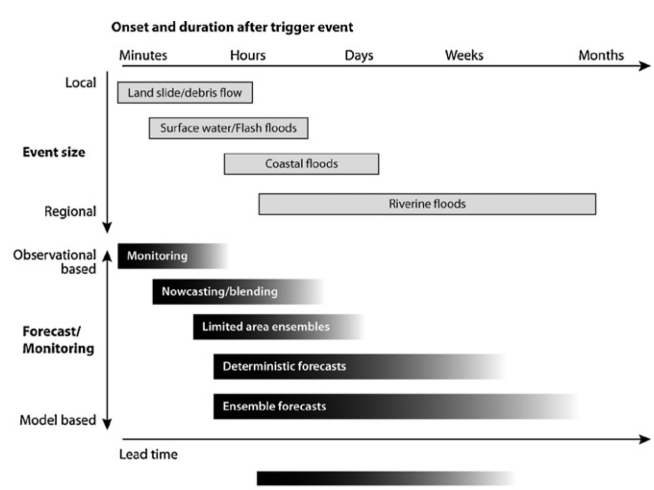



**Fig. 2 – Space-time scales of water-related hazards and meteorological products for forecasting and monitoring.**

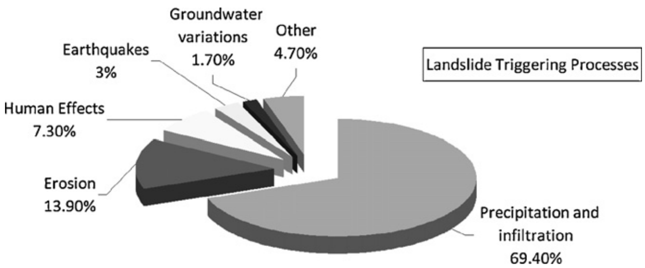



**Fig. 3 – Landslide triggers in Italy.**
***Source*: CNR-GNDCI AVI Database of areas affected by landslides and floods in Italy.**

of early warning for debris flows and rainfall-induced landslides is crossing information of land susceptibility, giving the "where" layer, with measurements or forecasts of severe rainfall events, providing the "when" layer (Hong and Adler, 2007). The duration of the accumulation period for rainfall producing landslides is linked to their depths. Short and intense events are usually related to shallow landslides and debris flows, while long lasting phenomena can mobilize deeper layers of a hillslope by raising their pore pressure.

Operational systems can be grouped, depending on their detection method, between empirical or physically based models (Capparelli and Versace, 2010). Empirical models are mostly based on a comparison of recorded or forecasted accumulated rainfall with corresponding threshold values. The latter are usually derived at regional scale whereas records of past events are available for calibration. Warning thresholds vary substantially depending on the location (Aleotti, 2004; Hong and Adler, 2007). National and regional systems often belong to this category, as no specific in situ monitoring is necessary. Physically based models aim at reproducing the physical behavior of the processes involved at the hillslope scale, and they require more information with higher level of detail. They are used to monitor local case studies with known instability issues.

As a result, a variety of systems are found in operation, with different level of complexity depending on the chosen model. On the one hand, simple procedures are of easier application to wide areas, but usually provide only the spatial location of possible instability phenomena. On the other hand, more detailed approaches can incorporate propagation models of the debris, enabling the evaluation of the risk, rather than just the hazard, by simulating potentially affected areas.

At the global level, it is worth mentioning the International Program on Landslides (IPL, see http://iclhq.org/), being an international initiative to coordinate cooperative research and capacity building on landslide risk mitigation. IPL contributes to the UN-ISDR and to the Hyogo Framework for Action 2005–2015 (United Nations, 2005), adopted at the World Conference on Disaster Reduction (WCDR) in 2005.

### 2.1.1. *Operational landslide and debris flow early warning*

Applications of landslides and debris flow early warning systems do exist since some decades, particularly in highly urbanized areas that have suffered for such hazards for a long time (e.g., Onodera et al., 1974; Keefer et al., 1987). Recent years have seen a considerable growth of operational systems at regional/country level, due to improvements and proliferation of measuring and monitoring networks, computing facilities, telecommunications, as well as increased awareness of natural hazards and future scenarios possibly affected by climatic changes. Some noteworthy examples are the Japanese early-warning system for debris flows and slope failures (Osanai et al., 2010), the Hong Kong Government's Landslide Warning System (see Chen and Lee, 2004), operational since 1984, and more applications such as in USA (Baum and Godt, 2009 and references therein), Brazil (Ortigao and Justi, 2004), New Zealand (Keys and Green, 2008), Taiwan (Kung et al., 2008), Canada (Jakob et al., 2006), among others.

Alarm systems for landslides and debris flows, based on NWP input, are not widely operated in Europe. Because of the very localized nature of landslides and debris flow events, the communities are usually responsible for crisis management at the local scale. Nonetheless, in some countries effort is put to coordinate multiple systems in a common platform, such as the IFKIS-Hydro in Switzerland (Romang et al., 2010). Among these, a debris flow alarm system is operative in the Illgraben catchment (Badoux et al., 2009), in the Rhone Valley, where warnings are spread through sirens and flashing lights at the major footpaths crossing the channel bed. Flash flood and debris flow events are detected by geophones installed upstream and the warning lead time, usually 5–15 min, only depends on the travel time of the flow. A similar system is operated for the municipality of Cencia (Dolomites, North-eastern Italy), based on an ultrasonic echometer which activates two traffic lights downstream in case hazardous flash flood waves or debris flows are detected. Further, critical rainfall thresholds have been derived from rain-gauge measurements during previous debris flow events (Bacchini and Zannoni, 2003). Alert situations are detected by comparing real-time rain rates with critical thresholds to support technicians managing the monitoring system and raise their preparedness.

An operational warning system for shallow landslides is run by ARPA Piemonte (Italy), monitoring the whole region since 2008. Results are shown in real-time on a graphical interface through a dedicated software module called SMART – Shallow landslides Movements Announced through Rainfall Thresholds (Tiranti and Rabuffetti, 2010). SMART is a model based on the exceedance of rainfall thresholds, and it is aimed at forecasting the time of occurrence of shallow landslides rather than the spatial location. The system was calibrated through a database of 160 landslides with hourly information of gauged precipitation and time of triggering. An extensive verification was performed considering more than 400 landslides in the period 1990–2002, by testing three different approaches for the estimation of critical thresholds. At the regional level, also the Italian region of Umbria operates a landslide EWS, by using both observed rainfall data from a dense hydrometeorological network and 72 h rainfall forecasts from a local scale meteorological model (Ponziani et al., 2010).

In Portugal, an EWS for precipitation-triggered landslides is being set up for the Lisbon region (Salameh et al., 2009). It is based on regional modeling of precipitation for central Portugal at fine-scale with the regional climate model WRF and a landslides alert model. The system was tuned with rain-gauge measurements and a database of more than 100 landslides. It is designed to predict the timing of the occurrences and their location at fine scale.

## 2.2. Surface water flooding and flash floods

Rain storms are highly hazardous to urbanized areas as they usually develop with strong winds and locally extreme rainfall rates which outweigh the soil infiltration capacity and the urban drainage potential, causing surface water flooding or flash floods. Those events occur on time scales ranging from minutes to few hours and typically affect limited areas up to few hundreds of square kilometers (Gaume et al., 2009). The main characteristic of flash floods and surface water flooding is their extremely sudden onset, resulting in very short warning times before an event. Although meteorological EWS are widespread tools available at the majority of national meteorological services across Europe, most of them have a space-time resolution rather coarse for a reliable prediction of surface water flooding and flash floods. The most common approach consists in comparing the latest rainfall forecasts, from numerical weather predictions, with reference thresholds often derived by statistical analysis on long term records of point measurements. The lag due to the hydrological processes involved is often too short for the implementation of effective warning procedures, as the hazard usually takes place in the same area where the rain storm occurs. Therefore, the lead time of the event detection basically depends on the forecast range of the NWP which, in turn, is generally related to the spatial and temporal resolution. Furthermore, warning performances have a decreasing trend with the forecast horizon, due to the inherent uncertainty in the initial conditions and the stochastic behavior of the atmosphere. In the past few years, an increasing number of weather forecasts have become available for use, each with specific spatial extent, space-time resolution and forecasting range. These products are mostly derived through NWP and by extrapolations from weather radar or satellite measurements (see, e.g., Table 1).

### 2.2.1. Operational surface water flooding and flash flood early warning

In the framework of the EMMA Program (European Multi-services Meteorological Awareness), the European network of national meteorological services, Eumetnet, developed the web platform Meteoalarm (http://www.meteoalarm.eu) to collect and display meteorological warnings from its national partners. The service provides 24–48 h lead time warnings for up to 10 weather parameters including heavy rain potentially inducing flooding, for 650 areas in 30 European participating countries. The website is freely accessible and the information is shown in a simple and clear way to be understood by non-technical users. Warning conditions are indicated in a map of Europe where areas are shown according to a traffic-light color-coding. Three warning levels are displayed, with increasing severity, in yellow, orange and red, while green means no warning situation. Although Meteoalarm is not specifically designed to provide early warnings for surface water and flash floods, it provides a harmonized and Europe-wide indication about regions at risk of weather-related hazards.

Among the partners joining the Meteoalarm network, some regional and national weather services took profit of European projects to create international partnerships involving scientific communities and end-users. The RISKMED project – Weather Risk Reduction for the Mediterranean (http://www.riskmed.net) gathered different partners from four areas in the Mediterranean Europe (Southern Italy, Malta, North-western Greece and Cyprus) with the aim of fostering the setup of warning systems for weather hazards, ready to run operationally also after the end of the project. A preliminary evaluation of the operational EWS in Cyprus is presented by Savvidou et al. (2009).

Some operational EWS for surface water flooding and flash floods rely on simplified indexes based on the concept of extreme conditions, with no need for additional calibration parameters. For example, the Extreme Rainfall Alert (ERA, Golding, 2009; Hurford et al., 2011) of the British Flood Forecasting Centre (FFC) and the Swiss warning system for point precipitation (Schmid and Wuest, 2005) were designed to give early indications on upcoming severe rainfall events potentially leading to surface water flooding. Similarly, the Extreme Forecast Index (EFI, Lalaurette, 2003) detects significant deviations of the probability distribution of global forecasts from the climatological mean, focusing on extreme values of rainfall, wind and temperature. The Probabilistic Flash Flood Guidance System (PFFGS) and the European Precipitation Index based on simulated Climatology (EPIC) (Alfieri et al., 2011) apply a similar concept by aggregating forecasted rainfall on hydrological units considering their river network. These systems enhance the detection of storms leading to flash flooding by using probabilistic forecasts in the very short range (PFFGS, 1–6 h lead time) up to the medium range (EPIC, 1–5 day lead time). Warning levels are displayed with return periods showing the spread of ensemble predictions (see an example in Fig. 4). The dissemination of alerts is being tested within a network of partners participating to the IMPRINTS (EC-FP7) project (http://www.imprints-fp7.eu) and further operational use of these approaches is envisaged.

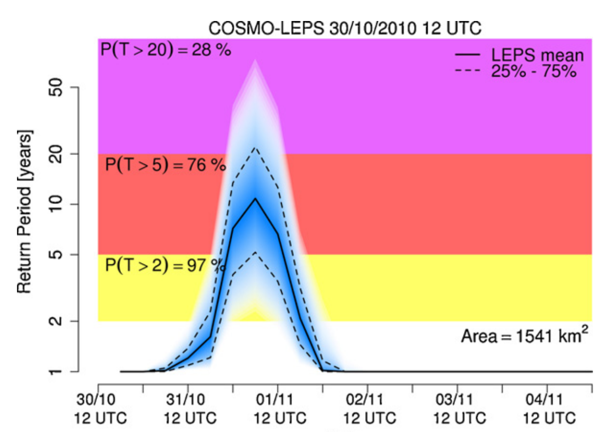



**Fig. 4 – Estimated return period from EPIC on 30/10/2010 12 UTC. Reported point in the Bacchiglione River near Padova, Italy, where severe flooding occurred on November 1st 2010.**

### 2.3. Coastal floods

Operational sea level monitoring and forecasting is common practice in most of marine and meteorological institutes across Europe. Numerical models for surge forecasting are based on the integration of the hydrodynamic governing equations, which are applied to closed domains and solved through finite difference or finite elements approach. Most storm surge forecasting systems are based on 2-dimensional vertically integrated models, while 3D simulations are usually adopted to study complementary variables such as water temperature, salinity, or the vertical structure of currents. However, the enhanced capabilities of modern computer facilities are facilitating the spreading of 3D models in operational centers.

The main objective of coastal flood warning systems is the accurate forecast of sea surface elevation. Warning thresholds depend at each location on the land topography and the location of infrastructures that may be disrupted in case of flooding. In harbors, it is also important to forecast anomalous low levels which can ground large vessels. Variations in the sea level are mainly due to the gravitational force of the sun and the moon, major responsible for tides, and to the atmospheric forcing of air pressure and low-level wind fields, which can produce storm surges and severe waves. These phenomena are often studied separately and summed up linearly, as their mutual interactions are negligible for a variety of cases. However, an increasing number of models account the coupling of waves, surges and tides to include non-linear effects (Lenhart and Pohlmann, 2004; Wolf, 2008).

While tide cycles are well known in advance, the quality of storm surge and wave forecast is conditioned on the quality of the weather predictions used as input. In fact, even whereas the latter represent minor contributions compared to the range of astronomical tides, they can cause serious coastal floodings if the peak timing of these events is in phase.

Operational storm surge forecasts based on weather predictions have been carried out for some decades in the Northern Europe (Flather and Proctor, 1983; Vested et al., 1992). Flather (2000) reviewed the main early warning systems for tides, storm surges and waves operational in the northwestern Europe in the early 1999. Further, in the framework of EuroGOOS, the European network contributing to the Global Ocean Observing System initiative, the SEPRISE project (EuroGOOS, 2007) collected an inventory of operational and pre-operational oceanographic models used in European centers in 2007, with the objective to keep it up to date.

#### 2.3.1. Operational coastal flood early warning

In Italy, the Centre for Sea Level Forecasting and Warning (ICPSM) of the Venice Municipality is responsible for storm surge prediction in the Venice Lagoon, which is known for suffering from frequent inundations. The ICPSM has set up an operational warning system (Bajo and Umgiesser, 2010) which uses Fast Artificial Neural Network (FANN) as a post-processor to a hydrodynamic finite element model called SHYFEM (Umgiesser et al., 2004), set up for the Mediterranean Sea. The system runs 5-day deterministic forecasts on a daily basis using mean sea level pressure and surface wind fields from ECMWF as weather predictions. Artificial neural networks were also applied successfully in Poland by the Institute of Meteorology and Water Management (IMGW) (Sztobryn, 2003), where the tidal range is small and wind storms are the main responsible for sea level variations.

Recently some national services have implemented ensemble forecasting in their warning systems, with the aim to better characterize the uncertainty of the meteorological forcing and possibly extend their warning lead time. The Storm Surge Warning Service (SVSD, de Vries, 2009) in the Netherlands is responsible for warning local authorities in case hazardous storm surge events are forecasted. Since 2007 the SVSD uses the ECMWF ensemble forecasts of surface wind and pressure as forcing to a two-dimensional shallow water model named WACQUA/DCSM98, simulating the sea water level for the following 10 days. Flowerdew et al. (2009, 2010) developed a forecasting system for coastal storm surges based on MOGREPS ensemble weather predictions (Bowler et al., 2008), which is used by the British Environmental Agency to issue warnings in England and Wales with lead time up to 54 h. In both these two systems, ensemble predictions perform better than deterministic ones for longer lead time (i.e., above 48 and 18 h respectively). For shorter lead times, the ensemble predictions showed underdispersion and some bias, so that higher resolution deterministic weather forecasts turn out more accurate.

Operational use of three-dimensional (3D) hydrodynamic models for storm surge early warning at country level is carried out in Germany, Denmark and Sweden (Gästgifvars et al., 2008). The Federal Maritime and Hydrographic Agency (BSH, http://www.bsh.de) in Germany and the Danish Meteorological Institute (DMI, http://ocean.dmi.dk/) adopted the same basic model code BSHcmod developed at BSH. Both systems run 3D model simulations in two configurations with different grid resolution. Further, a 2D coarse grid model named NOAMOD covering the north-eastern part of the Atlantic is used to account external surges possibly entering the North Sea. The BSHcmod model includes freshwater fluxes from 79 rivers mostly draining in the Baltic Sea, either simulated through hydrological models or climatological values, and open boundary conditions include tidal sea surface elevation.

The Danish version of the model, DMI-BSHcmod, is forced by DMI-HIRLAM (Källén, 1996) weather predictions. The 6 forcing parameters are 10-m wind speed and direction, mean sea level atmospheric pressure, cloud cover, surface air temperature and humidity. DMI-BSHcmod is run twice daily and provides ocean state forecasts with 15-min time step and 60-h lead time (see an example in Fig. 5). Sea level point observations are used to post-process the 'raw' model output by applying an auto-regressive filter method and alert conditions are derived accordingly. At BSH, predicted weather parameters are provided by the German Meteorological Service (DWD) and the sea level is forecasted with 72-h lead-time for the North Germany, including a tailored model for the Elbe estuary. Further descriptions and verifications of the warning systems in Denmark and Germany can be found in Kliem et al. (2006), Behrens and Günther (2009), and Müller-Navarra (2009).

At the Swedish Meteorological and Hydrological Institute (SMHI), the operational model HIROMB (Funkquist, 2001) was

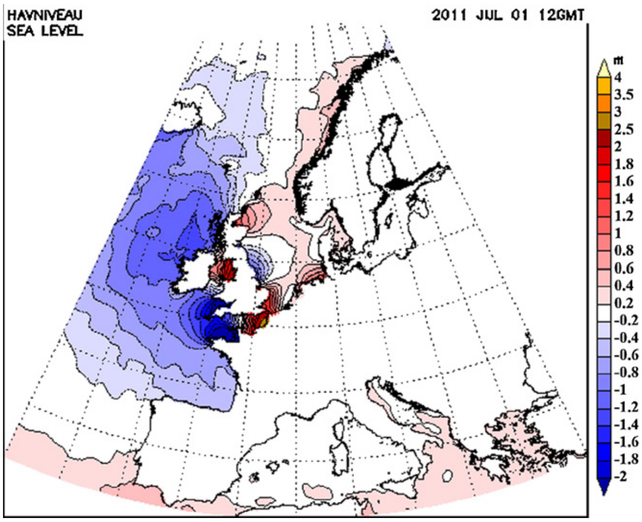



**Fig. 5 – 60-h ahead sea-level forecasts from DMI (http://ocean.dmi.dk/, © Danish Meteorological Institute).**

developed from the original BSHcmod code. It is run on a similar configuration to that used at DMI and BSH, by using SMHI-HIRLAM weather predictions as input.

Experiments with real-time assimilation of sea surface elevation in the forecasting models showed a reduction of the root mean squared error of the estimated values for the first hours of the forecast (Verlaan et al., 2005; Lionello et al., 2006). However, such approach requires a network of automatic gauges with data transmission capabilities and further a data quality control for possible gaps and corrupted measurements (see Verlaan et al., 2005). At present, the operational implementation of data assimilation is currently performed in few operational warning systems in Europe (e.g., SVSD), as the extent of the improvements achieved so far often does not justify the additional costs and resources to deploy. In Spain, the Nivmar storm surge forecasting system (Alvarez Fanjul et al., 2001) was developed by the Puertos del Estado and it is used on a daily basis for monitoring and warning purposes at country level, with forecast horizon currently up to 72 h. A simple data assimilation technique is implemented in Nivmar, which corrects for systematic errors in the mean sea level through a network of tide gauges named Redmar. Nivmar is based on the ocean circulation HAMSOM model, run twice daily with HIRLAM weather predictions as forcing.

## 2.4. *River floods*

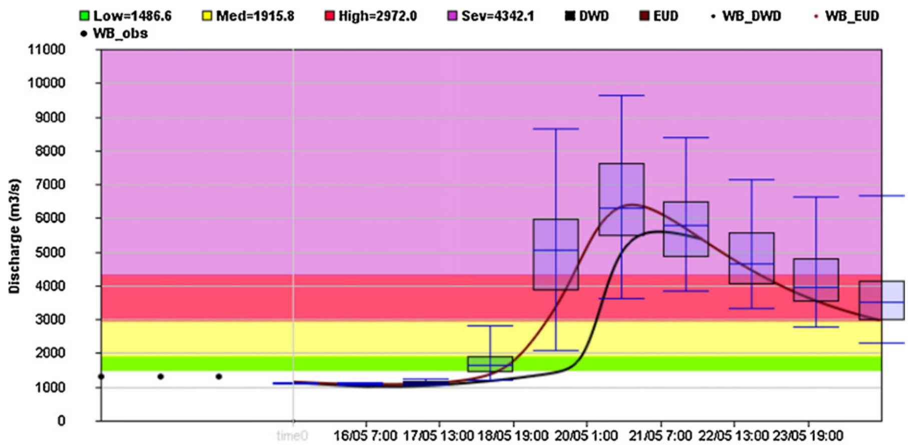
River floods are mainly caused by long lasting (i.e., ranging from hours to days) rainfall events or massive snow and ice melt, resulting in hundreds to several thousands of square kilometers of affected areas. The soil saturation and wave propagation play key roles in the flood dynamic, contributing to the long time scales typically related to this hazard. River floods can last up to various weeks when the flood wave is traveling downstream in large river basins, affecting also regions which have not been directly influenced by the heavy rain event which caused the flooding.

Monitoring river stages has long represented the simplest and most widespread approach for flood warning purpose. Several national and regional hydrological services in Europe operate quantitative river monitoring, which proves most beneficial in trans-boundary river basins and in other conditions when upstream rainfall information cannot be properly quantified. To further extend lead times in flood early warning, a number of institutes perform hydrological simulation of meteorological measurements or forecasts and compare output discharge or river stage with reference thresholds. Warning levels are usually derived from statistical analysis on historical measurements and displayed for selected river sections or through risk maps for different return periods. In case long term records of measurements are not available, reference thresholds can be assumed from recent recorded floods or estimated through regional approaches.

Warning lead-times for floods are highly variable, ranging from hours to weeks depending on the catchment characteristics and the meteorological input data. Firstly, rainfall events are drained by the catchment river network and become runoff with an average delay referred to as ‘‘catchment lag time’’, which depends on geomorphologic characteristics such as upstream area, elevation, slope and surface roughness, among others. Second, the use of weather forecasts as estimated input for rainfall, temperature and evapo-transpiration, allows an extension of the warning lead-time proportionally to the forecasting range. As suggested in the classical rational method (see e.g. Chow et al., 1988) the critical duration of extreme rainfall which produces design floods is of the order of the catchment time of concentration. It follows that large river floods are often induced by large-scale weather systems such as cyclones, which can be captured by NWP several days in advance. Recent developments have shown that operational ensemble forecasting is an effective way to tackle uncertainty analysis of weather predictions and thus to provide an improved measure of the risk of flooding (see e.g., Arheimer et al., 2011). A number of systems routinely use ensembles in flood early warning and a comprehensive review of such applications is described by Cloke and Pappenberger (2009).

### 2.4.1. *Operational flood early warning*

At the continental scale, the Joint Research Centre of the European Commission (EC-JRC) runs pre-operationally the European Flood Alert System (EFAS, Bartholmes et al., 2009; Thielen et al., 2009). EFAS aims at increasing preparedness for floods in trans-national European river basins by providing local water authorities with probabilistic flood warnings 3–10 days in advance. Distributed hydrological simulations are run on a 5-km grid with ensemble predictions of the European Centre for Medium-Range Weather Forecasts (ECMWF). Warnings are issued when (i) the probability of exceeding the 5-year return period discharge reaches critical values and (ii) results are confirmed by the two following ensemble forecasts. So-called ‘‘persistence diagrams’’ (e.g., see Fig. 6) were designed to summarize results from consecutive forecasts. Results from a long-term run on EFAS (Pappenberger et al., 2011) suggest that current ensemble NWP provide statistically valuable information for flood warning up to 30-day lead time. Further, recent




EUE > HAL

| Forecast Day | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2010051200 | | | | | | 1 | 5 | 22 | 33 | 31 | | | |
| 2010051212 | | | | | | | 5 | 19 | 28 | 29 | | | |
| 2010051300 | | | | | | | 2 | 22 | 34 | 38 | 35 | | |
| 2010051312 | | | | | | | 4 | 23 | 38 | 42 | 40 | | |
| 2010051400 | | | | | | | 3 | 20 | 43 | 47 | 46 | 42 | |
| 2010051412 | | | | | | | | 25 | 42 | 45 | 42 | 35 | |
| 2010051500 | | | | | | | | 11 | 42 | 48 | 50 | 49 | 45 |
| 2010051512 | | | | | | | | 45 | 51 | 51 | 51 | 48 | 40 |

EUE > SAL

| Forecast Day | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2010051200 | | | | | | | 1 | 8 | 21 | 20 | | | |
| 2010051212 | | | | | | | 2 | 8 | 20 | 22 | | | |
| 2010051300 | | | | | | | | 9 | 24 | 24 | 16 | | |
| 2010051312 | | | | | | | 3 | 15 | 28 | 27 | 16 | | |
| 2010051400 | | | | | | | 1 | 13 | 33 | 38 | 33 | 22 | |
| 2010051412 | | | | | | | | 6 | 28 | 31 | 21 | 10 | |
| 2010051500 | | | | | | | | 5 | 32 | 43 | 39 | 30 | 17 |
| 2010051512 | | | | | | | | 35 | 47 | 45 | 34 | 20 | 10 |

**Fig. 6 – EFAS 10-day flood forecast (top) on 15/05/2010 00 UTC for the Vistula River near Warsaw, based on two deterministic (DWD and ECMWF, solid lines) and one ensemble (ECMWF, box plot) weather predictions as input. Persistence diagrams are shown on bottom for High (red shadings) and Severe (purple shadings) alerts, indicating the number of ensemble members above each threshold, predicted in different consecutive forecasts.**

work by Alfieri et al. (2012) has shown promising results in the adaptation of EFAS for small scale catchments and flash flood early warning, through the use of a long-term reforecast dataset for deriving coherent warning thresholds at the small scale.

The severe flooding occurred in United Kingdom in summer 2007 urged the local government to improve all stages of the flood prevention and mitigation strategies (Haven, 2008). In 2009 the FFC was established from a working partnership between the Environment Agency and the MetOffice, which aims at providing a nationwide operational warning system for heavy precipitation and flooding. Regional and local forecasting systems were joined under a common platform, run by the National Flood Forecasting System in England and Wales, and the Flood Early Warning System Scotland by SEPA in Scotland (Werner et al., 2009). Similarly to the ERA, the Flood Guidance Statement (FGS) provides a qualitative overview, for the subsequent five days, on fluvial and coastal flooding in Great Britain, as well as extreme rainfall leading to surface water flooding. FGS is based on human-made decisions, with no numerical model to run hydrological simulations. However, it has the valuable property of providing flood risk estimates by crossing information on the probability of occurrence of severe events with the potential impact on the affected areas, by means of a flood-risk matrix. ERA and FGS alerts are not spread to the public but sent to a network of users referred to as Category 1 and 2 responders, mainly belonging to emergency services, local authorities and private sector bodies (e.g. utilities, transport companies).

Ensemble flood forecasting and early warning is performed at country level in Sweden, by the Swedish Meteorological and Hydrological Institute (SMHI), and in Finland, by the Finnish Environment Institute (SYKE). Both systems use 10-day ensemble forecasts from ECMWF as input to a semi-distributed hydrological model derived from the HBV model (Bergström, 1976). At SMHI, an EWS is operational since the early 1970s and a number of improvements have been performed to different parts of the forecasting chain over the years (Olsson and Lindström, 2008; Arheimer et al., 2011). A simple calibration method is applied to the ensemble percentiles to compensate for the underdispersion of the discharge spread towards a recorded dataset. The Finnish EWS was described by Vehviläinen et al. (2005). It is initialized with meteorological data from gauging stations and a network of weather radar with countrywide coverage. Further, water levels, discharges and snow depths are assimilated at several stations for real time correction. Hydrological forecasts for over 1300 rivers and lakes are updated several times a day and displayed on the web for public use at http://www.environment.fi/waterforecast.

In Switzerland, the Federal Office for the Environment (FOEN) issues hourly discharge forecasts for the subsequent three days, for several river stations within the Upper Rhine Basin (see Zappa et al., 2008). A similar system is operated since 2006 for monitoring and forecasting the water levels in the Lake Constance, shared between Switzerland, Germany and Austria. Further, a joint project (IFKIS-Hydro, Romang et al., 2010) was initiated in 2004 to set up a warning system for floods and debris flows in small-scale catchments within the range 1–1000 $km^2$. IFKIS-Hydro includes the recent operational flood warning system developed for the city of Zurich, based on hydrological simulation of ensemble weather forecasts for the Sihl River with lead time up to 5 days (Addor et al., 2011). The peculiarity of this case study is the presence of an artificial reservoir in the upstream part of the catchment, where water can be partly diverted to the Lake Zurich through a hydropower station and by-pass the basin downstream the dam. Current studies are focused on improving the decision support system by evaluating cost-loss functions of water spills for flood prevention in Zurich towards the economic losses due to reduced energy production.

A notable example of water-related multi-hazard warning system is that of the Piedmont region in the Northwestern Italy, developed and run operationally by the regional Environmental Protection Agency (ARPA Piemonte). A flood forecasting and early warning system is implemented since 2000 on the upper Po River, covering 37 000 $km^2$ across the Italian regions of Piemonte and Valle d'Aosta and the Swiss Canton Ticino (Rabuffetti and Barbero, 2005). The system, named FloodWatch, is based on hydrological simulation of numerical weather predictions with lead time up to 48 h. Estimated discharges are compared at a number of gauging stations to three warning levels of increasing severity and alert messages are sent to the Civil Protection in case hazardous situations are detected.

Many other operational river flood forecasting and early warning systems exist at country, regional or river basin level throughout Europe, having similar characteristics as the systems outlined above and providing publicly accessible flood warnings through the Internet. Some examples are the Czech Hydrometeorological Institute (http://hydro.chmi.cz), the French National Hydrometeorological and Flood Forecasting Centre SCHAPI (http://www.vigicrues.ecologie.gouv.fr/); the Norwegian Water Resources and Energy Directorate (http://www.nve.no); and the Romanian National Institute of Hydrology and Water Management (http://www.inhga.ro).

## 3. Discussion

An overview of the operational early warning systems described above, highlights a number of common points among systems developed by different institutions and for different hazard types. At the scientific and technical level, we have found a wide heterogeneity, with a relatively low proportion of operational systems relying on state-of-the-art-scientific approaches. In other words, despite being successful, several research findings are implemented into operational systems only after long time, mostly because of lack of communication between the scientific community and the institutions running operational systems. Further, for many applications no published document was available to describe the system setup and the warning methods. In most of these cases we referred to the web page of the institute responsible for the system.

### 3.1. *The use of weather predictions in current EWS*

Numerical weather predictions are the main input to most state-of-the-art systems, particularly because (i) they are available without gaps on a regular basis and on large domains, and (ii) they simulate the evolution of weather conditions in the future, thus enabling earlier preparedness and a possible reduction of the damage caused by natural hazards. Yet, some limitations do exist in the use of such products for operational systems:

- Small scale phenomena such as surface water flooding, landslides, debris flows and flash floods are usually caused by local rainfall peaks, whose extreme features are shown on space-temporal scales below the resolution of most available NWP. Besides, fine resolution NWP have wide uncertainty ranges, so results from deterministic estimates often lead to poor performance. As a consequence, early warning systems for such events remain a scientific challenge and only few approaches have been turned into operational systems. A possible solution to skillfully simulate small scale phenomena is the use of radar-derived nowcasting products or radar-NWP blending (see Table 1), which have increased accuracy and fine space-time resolution at the expense of shorter forecast horizon. Some of these products are provided in ensemble mode, which enables the estimation of the uncertainty of results.
- An additional difficulty in forecasting landslides is the correct estimate of their triggering time, as it is mostly influenced by the soil stratigraphy and the pore pressure in each layer. Therefore, the timing of slope failures can be

considerably delayed, if compared to the causative rainfall events, and also influenced by other parameters such as temperature and snowmelt. As a result, landslides EWS relying on NWP often produce false alarm rates higher than the detection rate (Osanai et al., 2010), thus limiting such systems to complementary monitoring tools for experts, rather than official alerting systems for widespread distribution. This leads many governments to favor local warning systems based on monitoring sensors, in those areas with ongoing mass movements that put at danger assets or human lives.

- Current trends in river flood and storm surge EWS denote an increasing use of ensemble weather predictions as input data. The simulation of sets of possible realizations of the system state is useful to derive information on the prediction uncertainty and proves most beneficial for longer forecast lead times. However, some studies (e.g., Flowerdew et al., 2010; de Vries, 2009) suggested that high-resolution deterministic NWP produce more skillful forecasts for the shortest time range.
- In most regions prone to coastal flooding (i.e., especially in the North-Western Europe), the magnitude of the tidal range is larger than that of storm surges and waves. Therefore the timing of atmospheric mass movements predicted by NWP is particularly important for a correct estimation of sea level extremes, which often occur when the peaks of these phenomena are in phase.

### 3.2. *What systems can learn from each other*

Because of the many similarities in the system structure and in the causative processes of the hazards, interconnections among different scientific communities are fundamental, as each of them can learn from the other. For example, systems for landslide early warning should interact closely with those for flash floods and surface water flooding, as they all work at similar space-time scales. Radar-NWP blendings at fine resolution already used by some applications for flash floods are rainfall products worth to be explored by other systems, both for improved capabilities in the short range and for better characterizing the initial conditions for river flood detection in the medium range. This latter, however, assumes a ''seamless'' prediction system to handle the transition from the short to the medium range. This is especially difficult in ensemble prediction, since local perturbations that govern the short-range forecasts may differ by those used in medium-range ensemble forecasts.

The fast response of landslide and debris flow warning systems and the automatic transmission of alerts is an effective way that can be used by other systems, such as for flash floods and surface water flooding, to maximize their warning lead time and reduce human errors due to stress and time pressure. However, the actual benefit is still questionable for river floods with longer lead times, where the added value of experienced forecasters' evaluation can significantly reduce the number of false alarms (Blöschl, 2008) by including complementary qualitative information (e.g., weather type, similarities with previous floods, variable average system skills for each location/river basin, state of flood protection measures etc.).

Ensemble forecasting is recognized as a major advancement in operational systems made possible by developments in numerical weather predictions. It is largely applied in river flood early warning and increasingly in storm surge forecasting. We believe that ongoing improvements of small-scale ensemble products will be extremely beneficial in flash flood and landslides applications.

Finally, the coastal flood warning community is a good example of coordination among different institutions and at different levels, where information is often displayed on the web and freely accessible to public and private users.

### 3.3. *Trends and challenges for future systems*

Recent natural disasters pointed out the need for integrated multi-hazard warning systems, operating on large supernational domains. A recurring situation is that of extreme rainfall events producing landslides and flash floods in the upstream catchments of a river basin, which may also induce severe river flooding downstream, possibly in different neighboring countries. Recent striking examples are the floods in central Europe in May 2010 and in Pakistan in summer 2010. A number of initiatives have already been promoted, which move towards international and multi-hazard forecasting and early warning, with the ultimate goal of integrated global systems. For flood-related hazards, global systems have been created or are being developed for extreme precipitation (WMO, http://severe.worldweather.wmo.int/), floods (NASA, http://trmm.gsfc.nasa.gov/; EC-JRC, daily runs operational since June 2011), flash floods (HRC, http://www.hrc-lab.org/giving/FFGS_index.php), landslides (Hong and Adler, 2007), and ocean state (Mercator Ocean, http://www.mercator-ocean.fr). Further, dedicated platforms have been set up for collecting information related to ongoing alerts, with the aim of improved coordination of humanitarian aids. Among them, the Global Disaster Alert and Coordination System (GDACS, De Groeve et al., 2006) developed by the European Commission (EC-JRC), provides near real-time alerts on natural disasters around the world and tools to facilitate response coordination.

Regarding flood warning in Europe, it is worth mentioning the European Flood Alert System (EFAS), which offers international coordination for floods in large trans-boundary river basins, in close collaboration with national water authorities and with the European Civil Protection (ECHO-MIC). At national level, the French rainfall-flood vigilance system is a notable example of inter-institutional coordination aimed at countrywide multi-hazard early warning system. Meteorological vigilance maps for the following 24 h are issued twice daily by Meteo-France, covering different types of weather extremes and recently including coastal floods. In addition, flood vigilance maps are published online by the Ministry of Sustainable Development through the collection of information from the several departments by the national forecasting center SCHAPI.

As discussed in Section 2, considerable advancements have been made in the recent years in the technical development of EWS, including increased use of ensemble predictions, establishment of sophisticated real-time monitoring networks, increasing of the spatio-temporal resolution of the models, among others. Future generations of early warning systems need to focus more on improving the visualization platforms and the dissemination of information and of alert situations. Indeed, increased availability and quality of data, approaches and computing facilities is leading to a growth of information to be communicated. In particular, critical information to assess and communicate should include location, hazard type, expected onset and duration, severity and probability of exceeding fixed warning thresholds (in the case of probabilistic forecasts), potential damage and affected population, among others. The use of alert maps is a widespread practice in many operational systems, with additional information attached to selected hotspots. A notable example is the Natural Hazards Support System (NHSS, http://nhss.cr.usgs.gov) of the USGS, which provides information on various natural hazards occurring both in the United States and around the world. Information needs to be well structured and effectively conveyed in an easy and understandable way. The overflow of information is detrimental to the system performance and adds up to negative effects of stress on decision-making under time pressure (Paton and Flin, 1997).

A further key step is the establishment of institutional bodies which ensure that early warning systems are well integrated into governmental policies and emergency management, both at national and local level. A proper integration of those systems at national and local level requires not only that information is easily accessible and understandable to all stakeholders, but also that resources are available for the actions to reduce risk and that management plans for these crisis situations exist. Finally, large effort needs to be put into training all stakeholders, including the population, on emergency procedures and safety measures following official alerts.

## 4. Conclusions

This work gives an overview of early warning systems for water-related natural hazards operational in Europe in 2012. Particular concern is given to those systems which use weather prediction input data and thus can detect extreme events with considerable lead time. Such systems provide useful early information which enhances population preparedness, enables damage reduction to assets, and improves the set up of emergency and recovery procedures.

This review aims to raise the awareness towards the increasing frequency and magnitude of natural catastrophes and, at the same time, to develop a culture of risk prevention through better knowledge of operational early warning systems. While a large number of operational EWS for water-related natural hazards exists and significant technical progress has been made so far, further work is required to exploit the benefits for risk reduction of such systems. Increased global interdependence underlines the necessity of cooperation, coordination and information exchange on EWS. Including EWS into policies and risk management plans, easily accessible and understandable warnings, and appropriate training ensures that those systems are properly integrated at all governmental levels. Stronger involvement of private and public stakeholders and additional information on hazard detection methods and performances are key factors to make people rely on warning systems and consequently benefit from them. This process requires more communication both to the public and within the scientific community as well. Indeed, there is need for more accessible and open information from the developers of warning systems, which should act themselves as promoter of their product. In this way, warning systems will become part of the cultural background and people will be better prepared to cope with emergencies.

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## Appendix A. Abbreviations

| | |
|---|---|
| ARPA | Agenzia Regionale per la Protezione dell'Ambiente (Regional Agency for Environmental Protection) |
| BSH | Bundesamt für Seeschifffahrt und Hydrographie (Federal Maritime and Hydrographic Agency) |
| DMI | Danish Meteorological Institute |
| DWD | Deutscher Wetterdienst (German Meteorological Service) |
| ECHO-MIC | European Commission Humanitarian Aid department – Monitoring and Information Centre |
| EC | European Commission |
| ECMWF | European Centre for Medium-Range Weather Forecasts |
| EFAS | European Flood Alert System |
| EFI | Extreme Forecast Index |
| EMMA | European Multi-services Meteorological Awareness |
| EPIC | European Precipitation Index based on simulated Climatology |
| ERA | Extreme Rainfall Alert |
| EuroGOOS | European Global Ocean Observing System |
| EWS | Early Warning System |
| FANN | Fast Artificial Neural Network |
| FD | Flood Directive |
| FFC | Flood Forecasting Centre |
| FGS | Flood Guidance Statement |
| FOEN | Federal Office for the Environment |
| FP7 | Seventh Framework Programme |
| GDACS | Global Disaster Alert and Coordination System |
| HAMSOM | Hamburg Shelf Ocean Model |
| HBV | Hydrologiska Byråns Vattenbalansavdelning |
| HIRLAM | High Resolution Local Area Modelling |
| HIROMB | High Resolution Operational Model for the Baltic Sea |
| ICPSM | Istituzione Centro Previsioni e Segnalazioni Maree (Centre for Sea Level Forecasting and Warning) |
| IFKIS | Interkantonales Frühwarn- und Kriseninformations-system (Intercantonal Early Warning and Crisis Information System) |

| | |
|---|---|
| IMGW | Instytut Meteorologii i Gospodarki Wodnej (Institute of Meteorology and Water Management) |
| INHGA | Institutul National de Hidrologie si Gospodarire a Apelor (National Institute of Hydrology and Water Management) |
| IMPRINTS | Improving Preparedness and Risk Management for Flash Floods and Debris Flow Events |
| IPL | International Program on Landslides |
| JRC | Joint Research Centre |
| MOGREPS | Met Office Global and Regional Ensemble Prediction System |
| NHSS | Natural Hazards Support System |
| NOAMOD | Northeastern Atlantic 2D model |
| NWP | Numerical Weather Predictions |
| PFFGS | Probabilistic Flash Flood Guidance System |
| PPEW | Platform for the Promotion of Early Warning |
| RISKMED | Weather Risk Reduction for the Mediterranean |
| SCHAPI | Service Central d'Hydrométéorologie et d'Appui à la Prévision des Inondations (French National Hydrometeorological and Flood Forecasting Centre) |
| SEPA | Scottish Environment Protection Agency |
| SEPRISE | Sustained, Efficient Production of Required Information Services |
| SHYFEM | Shallow Water Hydrodynamic Finite Element Model |
| SMART | Shallow Landslides Movements Announced through Rainfall Thresholds |
| SMHI | Swedish Meteorological and Hydrological Institute |
| SVSD | Stormvloedwaarschuwingsdienst (Storm Surge Warning Service) |
| SYKE | Finnish Environment Institute |
| UN-ISDR | United Nations – International Strategy for Disaster Reduction |
| USGS | United States Geological Survey |
| WCDR | World Conference on Disaster Reduction |
| WFD | Water Framework Directive |

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