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Design and evaluation of a site-specific flood early warning system: a case study in Blanes, Spain

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A case study in Blanes, Spain

Master of Science Thesis

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Abstract

Early warning systems (EWS) are key components of Disaster Risk Reduction strategies worldwide. However, several events have been reported in which warning messages have been accurately and timely disseminated, but severe damage and causalities still occurred. Failures in the early warning process have been linked to a lack of understanding by people at risk about the potential impacts of disasters and what they should do to mitigate their risk locally.

Past studies have indicated that the performance of EWSs could be improved by adjusting warning messages locally, describing potential impacts into warnings, involving communities at risk in the warning process, and giving instructions on how people could mitigate their risk locally. Although qualitative research has shown a general satisfaction with practices such as impact-based and community-based warning services, little experimental research has been conducted to evaluate the people's perceptions about EWSs based on such concepts.

Taking this into account, this work has designed, implemented and evaluated a flood EWS based on a novel framework for site-specific early warning systems (SSEWS). The framework was developed by CRAHI-UPC and promotes a community-based approach in which local stakeholders actively participate in designing and implementing the EWS. Furthermore, it features site-specific impact-based warning messages that include recommendations of self-protection actions.

In this case study, the SSEWS has been implemented in five vulnerable flood-prone specific sites in Blanes, Spain, with collaboration from local civil protection authorities and system end users. A randomised survey containing a hypothetical flood scenario was performed to compare the system end users' general perceptions and intended protective responses for two systems: the SSEWS and the current official Catalan EWS for weather-induced extreme events. This study analysed users' warning perceptions about the following attributes: understanding of the warning messages, understanding of possible flood impacts, understanding on how to respond to a flood event, risk perception, usefulness of warning and credibility. Results have shown that the SSEWS improved all warning perception attributes when compared to the current hazard-based warning service used in Catalonia, with statistical significance in all attributes. Moreover, the novel SSEWS has shown to statistically improve the system end users' intended protective responses to the hypothetical flood scenario in comparison to the Catalan official EWS. These findings suggest that introduction of practices such as site-specific impact-based warning messages coupled with behavioural recommendations in EWSs can improve public's response to disasters.

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List of Abbreviations

AEMET	Spanish Meteorological Agency
AIC	Aikake Information Criterion
AMS	Annual Maximum Series
BIC	Bayesian Information Criterion
CRAHI-UPC	Research Centre of Applied Hydrometeorology - Polytechnic University of Catalonia
ECWMF	European Centre for Medium-Range Weather Forecasts
EFAS	European Flood Awareness System
ERICHA	European Rainfall-Induced Hazard Assessment System
EWS	Early Warning System
FERP	Flood Emergency Response Plan
FRM	Flood Risk Management
GEV	General Extreme Value
GFDRR	Global Facility for Disaster Risk Reduction and Recovery
HBEWS	Hazard-based Early Warning System
HRES	High Resolution
IBW	Impact-based Warning
IFS	Integrated Forecasting System
IFWS	Impact-based Forecasting and Warning Serving
IMD	Indian Meteorological Department
METEOCAT	Meteorological Service of Catalonia
NHMS	National Hydrological and Meteorological Service
NWP	Numerical Weather Prediction
PDF	Probability Distribution Function
PoC	Proof of Concept

QPE	Quantitative Precipitation Estimate
QPF	Quantitative Precipitation Forecast
SMC	Meteorological Service of Catalonia
SSEWS	Site-specific Early Warning System
SSI	Semi-structured Interviews
UNISDR	United Nations Office for Disaster Risk Reduction
UN	United Nations
WMO	World Meteorological Organization
XRAD	Catalonia's weather radar network

CHAPTER 1

Introduction

This work aims to design, implement and evaluate a flood early warning system based on a novel framework for site-specific impact-based warning services. This chapter introduces the research by presenting a general background of flood early warning systems and the research problem statement. It also describes the research objectives and the research questions.

1.1 General background

Flood disasters have affected approximately 78 million people globally over the 20-years time frame between 1997 and 2016. Although countries have improved their flood risk management capacities, such events still cause significant direct and indirect damage worldwide (UNDRR, 2019). Early Warning Systems (EWSs) have been shown to reduce the loss of life and economic damages related to flooding disasters (UNISDR, 2006). Furthermore, it has been demonstrated that EWSs are economically competitive Disaster Risk Management soft measures. Pappenberger et al. (2015) estimated the potential economic benefits of EWSs as being of about 400 Euros to every invested 1 Euro.

In 2015, the Sendai Framework for Disaster Risk Reduction outlined targets for Disaster Risk Reduction to be considered by the United Nations members within the horizons of 2015-2030. This document highlighted the importance of enhancing EWSs by increasing people's access to disaster risk information (UNISDR, 2015). The strategic target g) of the Sendai Framework stated:

"(g) Substantially increase the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to people by 2030." (UNISDR, 2015, p.12).

There were several disasters in recent years in which early warnings were timely issued but the hazards still caused significant infrastructural damage and multiple casualties. According to the World Meteorological Organization (2015), a public inadequate response to early warning messages could be attributed mainly to a lack of understanding about the potential impacts of disasters. For example, the storm Gloria was an extratropical cyclone that hit mostly eastern Spain and southern France with heavy precipitations, causing several flash floods between the 19th and the 24th of January 2020 (AEMET, 2020). Prior to the event, the Spanish

Meteorological Agency (AEMET) issued several warnings regarding heavy rainfall, snowfall and strong winds (Pascual R., Cuevas G., Roa A., 2020). However, such early warnings were not sufficient to avoid the 13 deaths and the widespread infrastructural damages reported in Spain. According to a post-event report, the economic losses summed up to more than 500 million euros (OCCC, 2020).

Recently, catastrophic floods were reported in several European countries in 2021, with most of the casualties taking place in Germany. These floods have caused at least 196 deaths and widespread damage as of 20 July 2021. Reports indicated that some of the floods caused several deaths and devastating effects, even though forecasts of extreme rainfall and flood warnings were issued as early as four days before the events (Cornwall, 2021). Along with climate change, the failure of local flood early warning systems was pointed as the primary cause of the high reported death tolls. For example, a local newspaper stated that warning messages with instructions to evacuate or remain on higher floors did not reach enough people (France24.com, 2021).

In 2013, heavy rainfalls hit the Indian state of Uttarakhand two weeks before the start of the monsoon season of that year. The Indian Meteorological Department (IMD) issued accurate timely warnings for “very heavy rains”. However, a lack of understanding about the warning contents and the hazard impacts prompted inadequate responses by the authorities. The authorities declared that they were aware that “very heavy rains” were expected, but they could not visualise what impacts that hazard would bring. As a result, over 5700 people were reported dead (GFDRR, 2016).

Another example was the tropical cyclone Haiyan (Yolanda), a category 5 storm that hit The Philippines in 2014. The Philippine National Meteorological Agency issued accurate warnings for heavy rain and winds before the tropical cyclone Haiyan hit the country. Even so, the reports estimated that 6201 people died, 28626 were injured, and 1785 were missing. Once again, the authorities and the population knew in advance that a hazard would happen, but the lack of information regarding possible impacts resulted in a general ineffective response. In the previously mentioned examples, a better knowledge regarding potential hazard impacts and behavioural recommendations would likely have induced more effective responses, such as more extensive or sooner evacuations (WMO, 2015).

1.2 Problem statement

In order to address the gaps in the risk communication approach of current EWSs, several National Meteorological and Hydrological Services (NHMS) started experiencing a paradigm shift (Figure 1-1) from traditional hazard-based warning services towards impact-based warnings (IBWs). IBW services aim to convey to people and communities at risk what are the potential impacts of a hazard event along with the warning message. Basically, they provide the translation of technical hazard information into their likely impacts (WMO, 2015; GFDRR, 2016). In other words, IBWs focus on what a hazard will *do* rather than what a hazard will *be*. (Kaltenberger et al., 2020; Landaverde et al., 2020).

Several authors have suggested that adding a description of impacts alongside the warning messages could trigger more protective actions by individuals and, consequently, help to minimise the damages associated with floods and other types of disasters (GFDRR, 2016; Weyrich et al., 2018; S. Potter et al., 2021). Moreover, Basher (2006) concluded that visualizing hazard impacts could help communities to improve their risk mitigation strategies. Other authors have suggested that the efficiency of EWSs depended on a multitude of factors, but mostly on the understanding by individuals on how meteorological hazards could their lives (Pagano et al., 2002).

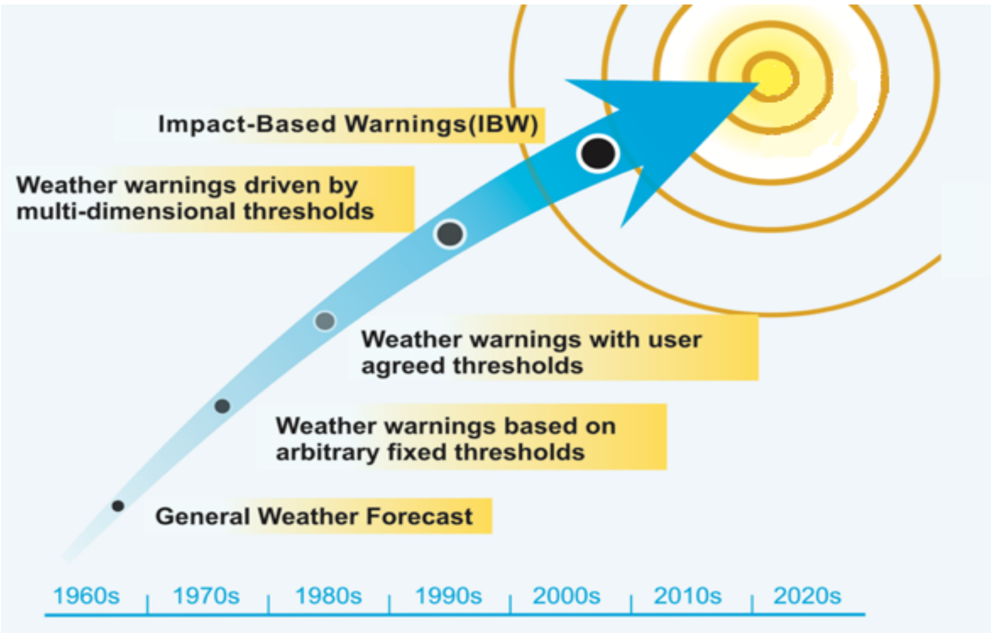


Figure 1-1 - Global evolution of Early Warning Systems. Source: Adapted from Meiyan et al. (2015)

Some authors indicated that EWSs could also be enhanced if they issued warning messages tailored to specific sites. For example, Shah et al. (2012) suggested that the introduction of location-specific information in flood warning messages would likely improve the efficacy of EWSs. Cumiskey et al. (2015) suggested that decentralizing EWSs by providing more localised warnings would deliver more beneficial information to the end users. Pagano et al. (2002) proposed that the use of forecasting and warning services in smaller regional scales could benefit the decision-making process in Disaster Risk Management.

Other studies indicated that implementing behavioural recommendations into warning messages increased the likelihood of people taking protective actions. For example, Casteel (2016) found the adding impact information and behavioural recommendations into warning messages increased the likelihood of people taking protective measures during emergencies. Weyrich et al. (2018) suggested that introducing impact information and behavioural recommendations into warning messages improved EWS users' risk perception and made them more likely to take protective actions.

Considering the mentioned failures associated with EWSs and the later practices proposed to improve warning services, the Centre of Applied Research on Hydrometeorology of the

Polytechnic University of Catalonia (CRAHI-UPC) has designed a novel prototype for a site-specific impact-based EWS for floods. This prototype is named hereafter as Site-Specific Early Warning System (SSEWS), and it was developed as part of the EU funded project ANYWHERE-2020 (Meléndez-Landaverde, Sempere-Torres and Berenguer, 2020). The SSEWS proposes a community-based early warning systeem tailored to specific sites, containing a description of potential flood impacts and behavioural recommendations that users could follow to mitigate their flood risk.

1.3 Objectives

Although qualitative research has shown a general satisfaction with EWSs' practices such as impact-based and site-specific warnings, little experimental research has been conducted to evaluate their operational feasibility. Therefore, this thesis's main objective is to ***design and evaluate a flood early warning system based on a novel methodology for site-specific impact-based warning services***. By doing so, this work aims to test the feasibility and explore practical applications of this novel framework. Furthermore, it expects to evaluate the risk communication approach proposed by this methodology.

The following secondary objectives support the main objective:

- Study the state-of-art of impact-based and site-specific flood warning and forecasting services.
- Assess impacts of past urban and river flood events in the case study location (Blanes, Spain).
- Identify flood-prone specific sites in Blanes and assess their local flood vulnerabilities.
- Calibrate impact-based warning thresholds to activate the warnings of the proposed EWS for each specific site.
- Define self-protection actions and link them to the EWS defined warning levels.
- Implement the designed EWS in a mobile application, which will be used to issue warnings to the system end users.
- Evaluate the proposed novel risk communication approach in comparison to the traditional hazard-based EWS used in Catalonia.

1.4 Research questions

This section describes the research questions that this study aims to answer**.**

Research question 1: Is it feasible to implement a novel framework for site-specific impact-based flood early warnings (SSEWS) in Blanes, Spain?

Research question 2: What are the requirements for transposing the SSEWS to other sites?

Research question 3: What were the main impacts of past urban and river flood events in Blanes?

Research question 4: Does the SSEWS Blanes citizens' warning perceptions when compared to a traditional hazard-based warning service?

Research question 5: Does the SSEWS improve Blanes citizens' intended protective actions when compared to a traditional hazard-based warning service?

CHAPTER 2

Literature Review

Early warning systems have been shown to effectively reduce loss of life and infrastructural damages related to disasters worldwide. However, effective early warning services depend not only on technical accuracy but on systems that involve actively those individuals and communities at risk. This chapter presents the context in which this research was done. It describes factors that can compromise the performance of early warning services and good practices found in the literature to overcome these challenges.

2.1 Early Warning Systems and their relevance

Early warning is a key component of Disaster Risk Management. According to a Global Assessment Report (GAR) on Disaster Risk Reduction made by the World Bank in 2011, improvements in EWSs in the United States were responsible for a significant reduction of mortality related to hazards such as floods, storms and heatwaves. From 1986 to 1999, the country experienced a reduction of 45% in mortality in approximately 15.000 tornado events, which was mainly attributed to improvements in early warning services (Rogers & Tsirkunov, 2011).

2.2 Components of an effective EWS

Although the benefits of EWSs are clear, their performance can be critically compromised if individuals and communities at risk are not actively involved in the warning process (UNISDR, 2006). Several events have been reported in which accurate hydrometeorological forecasting was produced, but EWSs could not effectively prevent loss of life and socio-economic damages due to failures in the warning response cycle. For instance, the performance of EWSs can be negatively affected if individuals receive a timely warning but do not know how to respond (WMO, 2015; GFDRR, 2016).

Mileti (1995) stated that the response to an early warning is a social process divided into five stages: hear, understand, believe, personalise and respond. Individuals who receive a warning normally have to go through a psychological process to create a personal meaning to the risk they are facing and what they should do before taking a preventive action. Issues in any stage of the warning response's cycle could hinder protective reactions by people, and consequently, negatively affect the entire EWS (Mileti, 1995).

In the last decades, it seems that there was a mismatch in the evolution of the technical components of forecasting and warning services and the EWSs' human factor. Fakhruddin et al. (2015) suggested that although technical features of forecasting services have improved through the advance of technologies such as ensemble forecasts, communication of risk in an understandable way by individuals and communities was normally neglected. Tapsell et al. (2005) also suggested that flood forecasting services have evolved in the past decades due to the advance of computer technologies. Nonetheless, the authors pointed out that a relevant weakness of EWSs was that the progress of forecasting services was not matched to advances in the dissemination of warnings. Frewer (2004) concluded that joining both physical and social sciences should be a major concern of Disaster Risk Management.

Perera et al. (2020) identified several challenges related to the effective dissemination and communication of warning messages in flood EWSs. According to the authors, the dissemination of warning messages in flood EWS usually follows a top-down approach. In this approach, forecasting agencies disseminate warnings to public authorities so they can further propagate them to the general public. However, it is very common that even though warnings are issued with enough lead time, they do not reach all the people who are exposed to the risk. Effective flood EWSs require that the right stakeholders receive the right information with enough lead time (Perera et al., 2020).

Besides issues in the dissemination stage of the early warning process, institutional barriers have been identified as obstacles to the successful implementation of EWSs. Marchezini et al. (2017) have explored the common institutional barriers to implement EWSs within the context of Brazil. The authors identified the following obstacles: centralised control of the national civil protection system; an approach of disaster risk management more focused on hazard than on impacts; centralised disaster data and information; and a poor dialogue between distinct fields of scientific expertise such as meteorologists, geologists, hydrologists, sociologists and researchers. Sukhwani et al. (2019) analysed which barriers affected the effective operation of flood EWSs, based on three practical examples of early warning services from Japan, Malaysia and Sri Lanka. According to the authors, institutional barriers have been identified in all three countries, and they have been considered to be critical to the performance of their EWSs. Such barriers included: a top-down approach, inefficient organizational arrangement, inadequate contingency planning, restrictive legislation and insufficient response capabilities.

Considering the previously mentioned barriers to the successful performance of EWSs, the United Nations Office for Disaster Risk Reduction (UNISDR) proposed a checklist that could be used to evaluate their efficacy. According to the UNSIDR, an efficient EWS should be composed of four inter-related components: risk knowledge, monitoring and warning, dissemination and communication, and response capability (Figure 2-1). Deficiencies in each of these elements could undermine the overall system's efficacy (UNISDR, 2006). This means that the warnings should reach all those at risk, and they should be clear and useful. In order to trigger a protective response by individuals, it was considered critical that people understood the threats they were exposed to (Macherera & Chimbari, 2016).

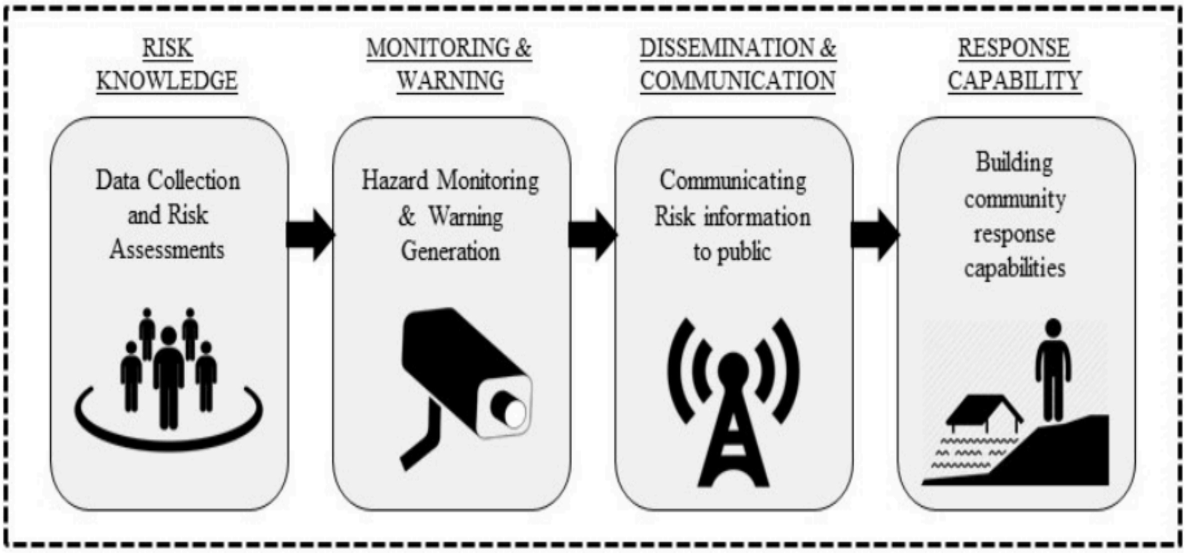


Figure 2-1 - Four components of an effective EWS. Source: (Sukhwani et al., 2019).

The first component proposed by the UNISDR implied that hazards and vulnerabilities should be well understood, as well as their patterns. The early warning service should implement a systematic procedure for collecting, assessing, and disseminating data, maps and trends on hazards and vulnerabilities (UNISDR, 2006; Cumiskey et al., 2015). The second component proposed the establishment of a monitoring and warning service with a solid scientific and technical foundation. The third component suggested the introduction of dissemination systems that would effectively alert individuals and communities of upcoming disasters, as well as tools to allow national and regional coordination, and data exchange. The fourth component was related to enhancing the ability of communities to respond during emergencies through the improvement of preparedness, risk education and community involvement (UNISDR, 2006).

2.3 Good practices of EWSs

This subsection explores practices that previous studies have shown to potentially improve the performance of EWSs. The foundation of the Site-Specific Early Warning System framework presented in this thesis was conceptually designed in four core principles: people-centred approach, impact-based warnings, site-specific warnings, and behavioural recommendations in the warnings messages. Each of them will be further discussed.

2.3.1 People-centred approach

Several authors suggested that social and psychological factors strongly influence the performance of EWSs. For example, Tapsell et al. (2005) identified factors that could affect the social performance of flood warning communication services. According to the authors, the performance of warning services could be affected not only by the type of warning technology but also by the warning recipients' characteristics, such as socioeconomic status, previous experience with floods, disability and age. Twigg (2003) analysed how the human factor affected early warning services and concluded that the perception of disaster risk varied on an individual basis. The author stated that the risk perception of EWSs' users was affected by psychological, social, institutional, and cultural biases.

Based on these findings, there has been a surge in the interest of developing EWSs focused on people. According to the UNISDR (2006), effective EWSs should actively involve the populations exposed to risk and promote education to improve people's risk understanding. Macherera and Chimbari (2016) stated that a community-based EWS was characterised by active participation of the community in the stages of data collection, design and system operation. Basher (2006) indicated that EWSs for disasters should not only have a solid scientific and technical foundation but should also focus on the people at risk. Zschau & Küppers (2013) stated that effective EWSs needed to couple technical abilities of hazard forecasting and efficient communication approaches with the active collaboration from local communities. The authors indicated that successful EWSs depended on the cooperation between several levels of activity, which should be tied together in timely communication. Sai (2016) stated that an active local community participation in EWSs was linked to all the four components of effective EWSs proposed by the UNISDR.

Previous research has shown a trend in Disaster Risk Management in recent years towards more people-centred approaches (Scolobig et al., 2015). As a result, the emphasis has shifted from a top-down, command-and-control management style to a more bottom-up, user-oriented Disaster Risk Management (Basher, 2006; UNISDR, 2006). The Sendai Framework for Disaster Risk Reduction also advocated using a more people-centred approach for EWSs in its guiding principle 33 (b). The framework defined this effort as a priority to be taken in the horizons 2015-2030. The guiding principle 33 stated:

"(b) To invest in, develop, maintain and strengthen people-centred multi-hazard, multisectoral forecasting and early warning systems, disaster risk and emergency communications mechanisms, social technologies and hazard-monitoring telecommunications systems; develop such systems through a participatory process; tailor them to the needs of users, including social and cultural requirements, in particular gender; promote the application of simple and low-cost early warning equipment and facilities; and broaden release channels for disaster early warning information;" (UNISDR, 2015, p.21)

2.3.2 Impact-based warnings

In recent years, there has been a shift in warning services from systems focusing on hazard conditions alone to systems that would include impact information in the warnings. This shift was endorsed by the World Meteorological Organization (WMO), which published guidelines to help NHMSs improve their forecasting and warnings services by shifting to IBWs (WMO, 2015). In this work, IBWs refer to warning messages that contain information of potential impacts of a forecast hazard, with a description of an expected damage scenario. IBWs implementation is currently a priority for the NMHSs of the WMO member countries (GFDRR, 2016). Recently, it was stated that most European NHMSs were migrating or aimed to migrate from traditional hazard-based warning services to IBWs (Kaltenberger et al., 2020).

Although little research has been conducted on IBWs, there seems to be a general satisfaction from previous authors regarding this type of warning service. The WMO addressed the following positive aspects associated with the introduction of IBWs: better contingency planning; impact information provides wider social benefits; additional information could facilitate the decision-making process; and impacts information increases common situational awareness (WMO, 2015). Potter et al. (2021) studied the benefits of introducing IBW services for severe weather EWSs based on perspectives of weather and disaster management agencies from New Zealand and Europe. According to the authors, the benefits of IBWs included a perceived improvement in the public's comprehension of potential consequences of a hazard, improved forecasters' awareness of antecedent conditions, enhanced interagency communication and a potential reduction in false alarms.

Some studies indicated that adding impact information in warning messages increases people's risk perception and their chances of taking protective actions in disasters. For example, Casteel (2018) has performed experiments to evaluate if people would be more likely to take a protective action as sheltering if impact information was added to tornadoes early warning messages. The authors concluded that the addition of impacts information into the warning messages increased people's likelihood to take protective actions in three out of four hypothetical scenarios. Morss et al. (2016) compared hazard-based and IBWs through a survey containing a hypothetical scenario of an upcoming hurricane. The study found that introducing impact information in the warnings slightly increased people's intended protective actions and risk perception. Meléndez-Landaverde et al. (2020) compared hazard-based warnings to IBWs in nine hypothetical flood scenarios. According to the authors, the addition of impact information into the warnings increased people's likelihood of taking a protective action in all analysed scenarios.

2.3.2.1 Criticism of impact-based warning services

On the other hand, other authors pointed out benefits of IBW messages but indicated that their use not necessarily led to more protective actions by individuals. Potter et al. (2018) examined how impact-based warnings for severe weather events influenced individuals' risk perception and intended protective responses through a survey based on a hypothetical scenario of strong winds. According to the authors, adding information referent to impacts into warning messages increased people's concern, sense of threat and understanding of possible impacts. However, the authors found that the increase in risk perception did not lead to a higher likelihood of taking protective responses. Mu et al. (2018) studied how different formats of weather warnings affected people's intended protective actions. They concluded that, in general, adding more information such as impacts description to weather warnings was considered to be usually beneficial and to increase people's trust in warning services, but did not necessarily lead to more protective actions.

Furthermore, some authors have also identified challenges in the implementation of IBW services. For example, Kaltenberger et al. (2020) found that the successful implementation of IBWs could be hindered by obstacles such as the lack of impact data, technical resources, and organizational issues. Potter et al. (2021) identified challenges such as lack of impact data, institutional conflicts in roles and responsibilities, and an increased load on organizations to provide impact information to forecasters with little perceived return. The authors also identified as potential challenges the need to determine if systems should be built for individuals or communities and the possibility of issuing contradicting warnings. Nonetheless, the authors mentioned that little research had been conducted on the evaluation of the feasibility of IBWs operationally and institutionally.

It can be concluded that the main challenges of IBWs seem to be related to institutional barriers and lack of impact data. As stated by the WMO (2015), strong collaboration and partnerships between stakeholders are crucial elements to guarantee the success of IBWs and overcome the institutional challenges related to their implementation. The SSEWS proposed in this work aims to tackle the issue of lack of impact data by designing warning systems tailored to specific vulnerable sites, in which impact data collection would be more reasonable.

2.3.3 Site-specific warnings

Considering that the flood vulnerability is highly dynamic in space, authors have suggested that EWSs could be enhanced by adjusting warning messages locally. For example, Cumiskey et al. (2015) have highlighted the importance of decentralizing the process of generating and disseminating warnings in order to provide more useful information to end users. Oktari et al. (2014) stated that warning messages should be tailored to specific geographic regions, so they could reach those people who were at risk. Rossi et al. (2018) identified good practices for public EWSs for weather-related hazards. According to the authors, the understanding of site-specific vulnerabilities was identified as a good practice which was also directly linked to the people-centred approach of EWSs. Shah et al. (2012) concluded that the efficacy of EWSs could be enhanced by providing users with location-specific warnings, so they could easily link the warning messages to their local context. The International Federal of Red Cross (2012) published guiding principles for implementing effective community-based EWSs. In the guiding principle number 5, it was highlighted the importance of designing EWSs tailored to the needs of local communities.

Most operational site-specific EWSs found in the literature for disasters were designed for landslides due to the localised nature of the phenomena (Michoud et al., 2013; Chaturvedi et al., 2017; Gian et al., 2017). However, site-specific warnings are also pertinent within the context of flash flooding forecasting and warning services due to the usually localised nature of such phenomenon. As stated by Younis et al. (2008), the climatic conditions that cause flash floods are generally severe convective systems that form under potentially unstable conditions caused by localised trigger mechanisms.

2.3.4 Warnings with behavioural recommendations

The concept of behavioural recommendations to be followed in case of emergencies is not new in the Disaster Risk Management field. As early as 1995, Mileti stated that warning messages should include clear statements guiding people's responses. According to the author, it was not reasonable to assume that the general people would know which protective actions to take after receiving a warning. Such protective actions should be described in the warning message. Shah et al. (2012) analysed which factors influenced flood warning responses of farmers in Bangladesh. They concluded that adding advisories into warning messages increased the likelihood of farmers in Bangladesh of taking protective responses to flood events.

Casteel (2016) also studied the effects of adding both impact information and behavioural recommendations in warning messages. He found that implementing this type of information led to more protective responses by people. Weyrich et al. (2018) analysed individually the effects of adding behavioural recommendations in the content of warning messages through an online survey based on a hypothetical thunderstorm event. According to them, people who received warnings that contained behavioural advice indicated that the warnings were clearer, simpler to comprehend, and more credible than those who received warnings without such advisories.

2.4 Operational approaches to EWSs

This section presents operational approaches of early warning services to weather-induced events for a specific type of flood phenomenon (flash floods) and a type of warning service (impact-based warnings).

2.4.1 Flash floods

Flash floods are characterised by rapid events with short timescales. The National Weather Service of the United States (2021) classified a flash flood as any event occurring within 6 hours after the rainfall occurred. Urban flash floods are usually caused by localised intense rainfall events that overcome the capacities of drainage systems of urban areas (Alfieri et al., 2012). River flash floods typically occur when heavy rainfall events surpass the drainage capacity of river catchments, but they can also occur due to snowmelt or to structural failures such as dam breaks. Most fatalities due to floods in the United States are caused by flash floods (NWSUS, 2021).

Due to the short timescale of flash flood phenomena, most flash flood warning and forecasting services consist of a rainfall-thresholds based approach in which there is typically no need to perform time-consuming hydrological modelling. Alfieri et al. (2012) performed a review of the operational European EWSs for extreme weather-induced events, including urban flash floods and river floods. According to the authors, urban flash floods usually occur in very small spatial scales of up to a few hundred' square kilometres and time scales of up to a few hours. Furthermore, they sated that most meteorological tools available in Europe had a relatively coarse space-time resolution for an adequate forecasting of urban floods. The authors indicated that the primary approach for urban flash floods forecasting and warning services consisted of using reference rainfall thresholds derived from statistical analysis of long-term rainfall data records. Alfieri et al. (2018) identified three flash flood warning and forecasting services based on rainfall thresholds used in Europe. All three systems were based on the same general approach, which consisted of comparing values derived from rainfall forecasts and nowcasts to reference values obtained from long-term data extreme frequency analyses.

In the United States, the National Weather Service has been using the Flash Flood Guidance System (FFGS) for many years as a tool for flash flood warning services. The FFGS has been developed by the Hydrologic Research Center of San Diego, California, and it might be the most prominent example of a rainfall thresholds-based system for flash flood forecasting. The system is based on the concept of the Flash Flood Guidance (FFG), which is an index that indicates the amount of rainfall needed over a certain duration of time to cause flooding within a small catchment (WMO, 2015). The system considers antecedent moisture conditions by storing information about the amount of rainfall that has already entered a catchment. A flash flood warning is issued when the system identifies a forecast or nowcast indicating a higher amount of rainfall for the catchment than the FFG. Therefore, the system can be characterised by a deterministic forecasting and warning service based on variable rainfall thresholds (Ntelekos et al., 2006).

2.4.2 Impact-based warning services

IBW services are still a relatively new approach which is in an early stage worldwide. In the United Kingdom, the Met Office implemented IBW services within the National Severe Weather Warning Service (NSWWS) in 2011. This happened after studies conducted by the Met Office indicated that although forecasting and warning services in the UK were fairly accurate, their effectiveness was negatively affected due to a lack of information on impacts and recommendations on how to mitigate risk (Harrowsmith, 2015). The Met Office currently issues warnings based on a colour-coded levels classification derived from the risk matrix found in Figure 2-2.

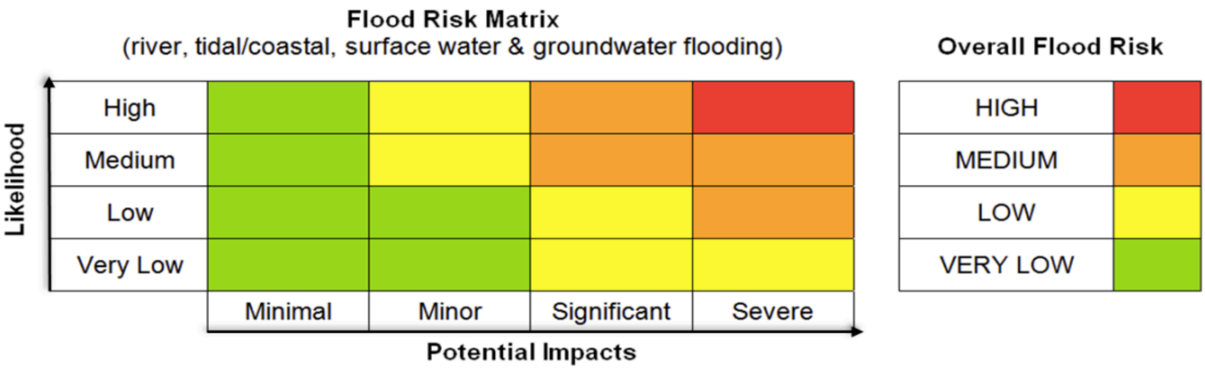


Figure 2-2 - Risk matrix used by The UK Met Office

The risk matrix used by the British Met Office considers both the likelihood of occurrence of an event and the expected impacts if the event happens. The likelihood axis describes the forecasting uncertainty and it is linked to aspects such as the forecasting lead time. For example, higher lead times are associated with more uncertain forecasts and lower lead times to more certain forecasts. The impacts axis describes the expected impacts of a potential event, which are defined for different regions according to the local vulnerabilities. For example, the same hazard (e.g. wind gusts of 70 mph) would cause different impacts in London and Northern Scotland (Harrowsmith, 2015).

In Europe, the European Meteorological Network (EUMETNET) implemented the MeteoAlarm, a service that provides information related to extreme weather events in several countries. The MeteoAlarm provides a web service (meteoalarm.org) that contain information about different types of hazards, such as floods, rain, wind, snow, thunderstorms, etc. (EUMETNET, 2021). The type of warning message varies according to the NHMSs which emits it. According to Kaltenberger et al. (2020), 34% of the countries who participated in the Meteoalarm at the time emitted IBWs, 34% emitted IBWs for only some parameters, and 41% did not issue IBWs. Figure 2-3 presents an example of an IBW for strong winds issued by the Météo-France (part of Meteoalarm), which includes both potential impacts and instructions on how to respond to the hazard.

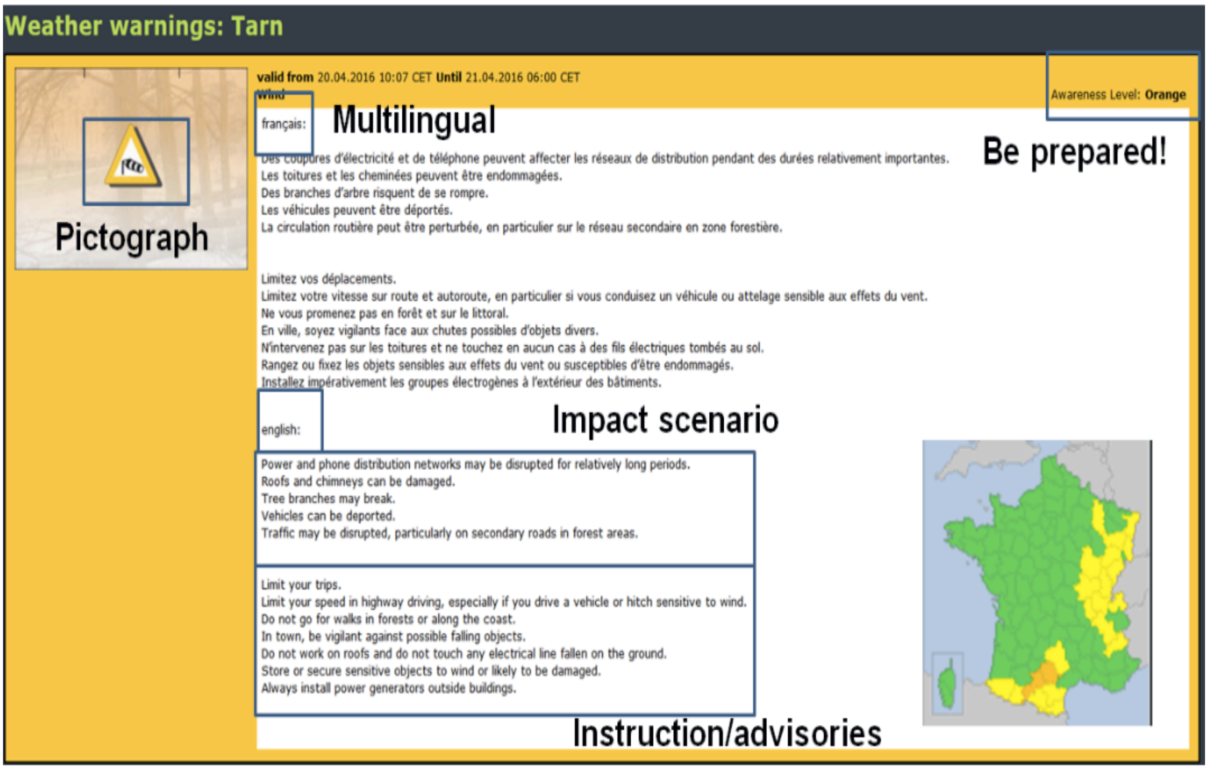


Figure 2-3 - Example of impact-based warning message from Meteoalarm. Source: Kaltenberger et al. (2020)

In the United States, the National Weather Service developed an IBW service to improve the public's response and decision-making process during disasters. Initially, the service was designed in 2012 for tornadoes, but later, it introduced other types of hazards as well. In 2019, the National Weather Service incorporated IBWs for flash floods in all its offices. The warning messages include descriptions of the hazard, source, potential impacts and precautionary actions to be taken to mitigate flash flood risk (NWS, 2019). Figure 2-4 presents an example of an IBW for flash floods issued by the U.S. National Weather Service, which includes both potential impacts and instructions on how to respond to the hazard.

```
...FLASH FLOOD EMERGENCY FOR LIFE-THREATENING CATASTROPHIC FLOODING...

The National Weather Service in League City has issued a

* Flash Flood Warning for...
  Northeastern Austin County in southeastern Texas...

* Until 715 PM CDT.

* At 119 PM CDT, Doppler radar indicated continued bands of rain and
  thunderstorms across the area. Emergency management reported ongoing
  water rescues. Rainfall rates of 2 to 3 inches per hour will persist
  across the warned area.

  This is a FLASH FLOOD EMERGENCY FOR LIFE-THREATENING CATASTROPHIC
  FLOODING. This is a PARTICULARLY DANGEROUS SITUATION. SEEK HIGHER
  GROUND NOW!

  HAZARD...Life-threatening flash flooding caused by thunderstorms.

  SOURCE...Emergency management.

  IMPACT...Widespread, life-threatening flooding will continue and
           perhaps worsen at some locations. Historic flooding is
           expected to continue in the Houston metropolitan area through
           the foreseeable future.

* Some locations that will experience flooding include...
  Pasadena, Pearland, League City, and Humble.

PRECAUTIONARY/PREPAREDNESS ACTIONS...

Move to higher ground now. This is an extremely dangerous and
life-threatening situation. Do not attempt to travel unless you are
fleeing an area subject to flooding or under an evacuation order.

&&

LAT...LON 2904 9515 2905 9527 2932 9536 2916 9543

FLASH FLOOD...OBSERVED
FLASH FLOOD DAMAGE THREAT...CATASTROPHIC
EXPECTED RAINFALL...2-3 INCHES PER HOUR
```

Figure 2-4 - Example of impact-based warning message issued by the U.S. National Weather Service. Source: NWS (2019)

CHAPTER 3

Case study

This chapter presents a brief description of the study area and discusses why it was chosen. It also describes the specifications of the data set used to perform this research. At the end of this section, the current official early warning system for weather-related events in the study area is described.

3.1 Study area description

The study area of this research is the coastal town of Blanes, located in Catalonia, Spain. Blanes lies on the southern edge of the region known as *Costa Brava*, one of the top touristic destinations of the European Union (Albayrak et al., 2018). The municipality is located between the Mediterranean Sea and the foothills of the Catalan Coast Range, a mountain range running parallelly to the sea in Catalonia (Santanach, 2013). In 2020, Blanes had a population of 39.914 inhabitants and an area of 17,66 km^2 (Instituto de Estadística de Cataluña, 2021). Figure 3-1 presents the location of Blanes in Spain.

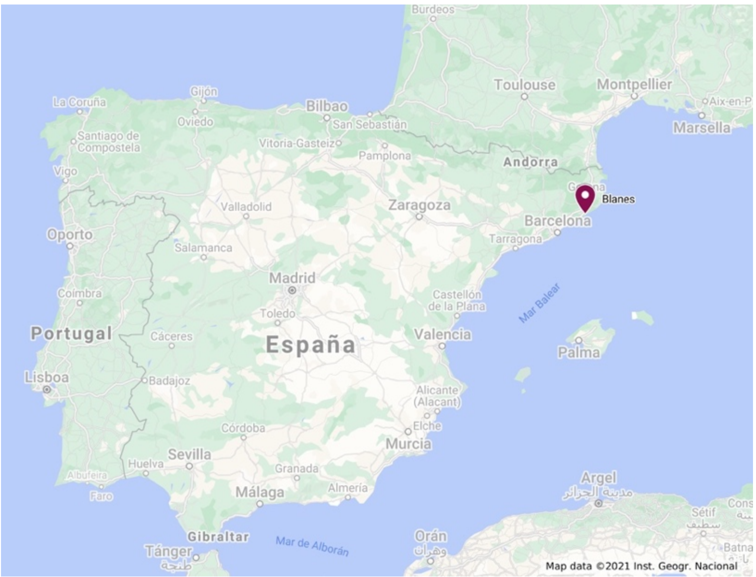


Figure 3-1 - Location of Blanes in Spain.

The most important fluvial course in Blanes is the Tordera River, which has its delta located in the southwestern part of the municipality. The Tordera River has approximately 53,5 km and its catchment drains an area of approximately 876 km^2 (Urgell i Vidal, 2008).

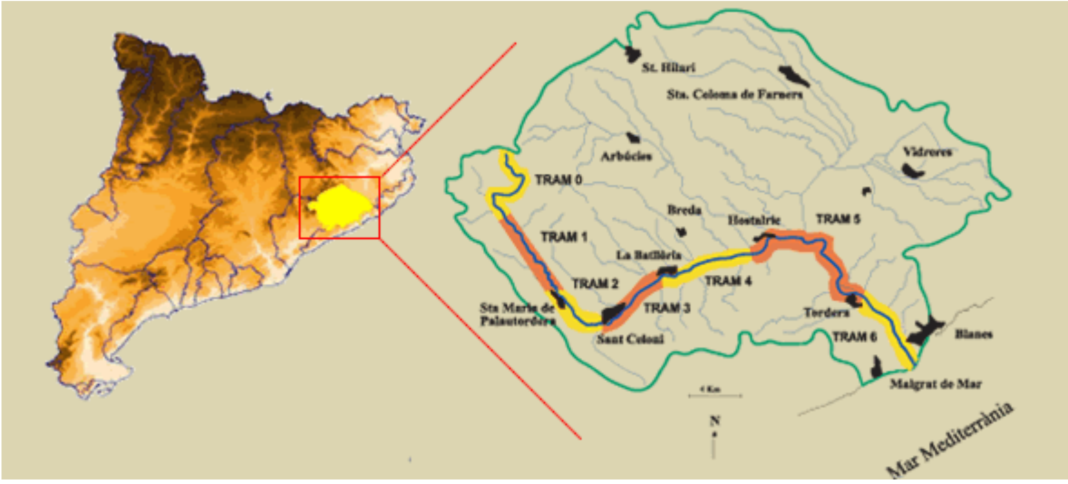


Figure 3-2 - Location of Tordera catchment in Catalonia, Spain (Urgell i Vidal, 2008).

Although the Tordera is the largest watercourse in the municipality, past flood events were also reported at the stream Plantera and the stream Blanes. These streams have their source at the Catalan Coastal Range and they flow to the Mediterranean Sea. They have suffered several man-made alterations in their original routes to fit structures such as roads and railways. Furthermore, these streams are covered in most of the areas in which they cross the town of Blanes. The stream Plantera is covered in its last 1480 m and the stream Blanes is covered in its last 910 m before flowing to the Mediterranean Sea. For both streams, the maximum flow capacity in their covered sections corresponds to a return period of 100 years (Ajuntament de Blanes, 2016).

Figure 3-3 - 500-years flood extension of the Tordera river in Blanes (Blanes, 2016)

Figure 3-3 presents the extension of the 500-years flood in the Tordera River in Blanes and the position of the streams Plantera and Blanes within the town. The green dotted lines indicate the covered sections of these streams.

The selection of Blanes as the study area of this research was mainly due to its flood vulnerability to both urban flash floods and river floods. According to the Special Emergency Plan for Floods in Catalonia, the municipality of Blanes has a very high flood risk, as can be seen in Figure 3-4 (ACA, 2017). Another reason was the availability of operational forecasting services for the area within the scope of the project ANYWHERE, funded within the EU's Horizon 2020 research and innovation programme (ANYWHERE, 2021). Finally, the prompt availability from the local civil protection body helped to implement and validate the SSEWS framework in the municipality.

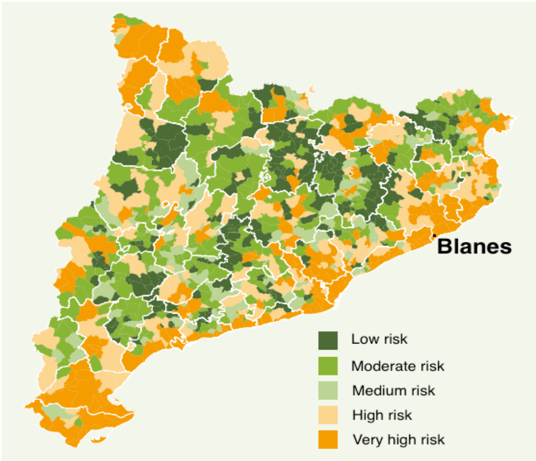


Figure 3-4 - Map of flood risk in Catalonia. Source: Adapted from Catalan Water Agency, 2017.

3.2 Climate and topography

Blanes is characterised by a typical Mediterranean climate with hot, dry summers and cooler winters. According to the Thornthwaite climate classification, the municipality has a dry-subhumid (C1) climate type (Thornthwaite, 1948; Ajuntament de Blanes, 2016). July is usually the driest month, and October is generally the wettest month. During the dry summer months, most precipitation occurs as frontal rainfalls (Ayuntamiento de Blanes, 2008). The average annual precipitation ranges from 600-700 mm and the average yearly temperature is between 15º and 16º C. (Matas, 2013) Figure 3-5 presents the average monthly precipitation in Blanes.

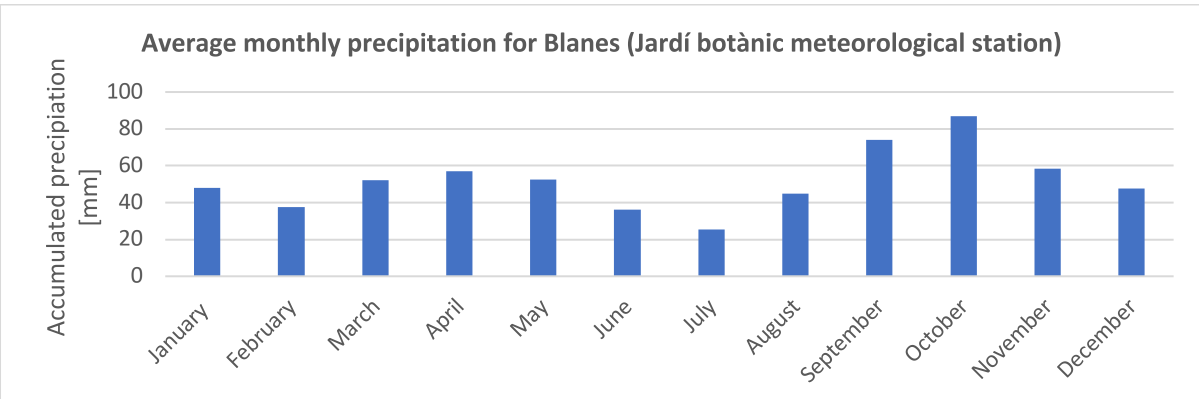


Figure 3-5 - Average monthly precipitation at Jardí Botànic station, Blanes (1969-2017). Elaborated by the author. Data source: AEMET.

Although Blanes has a relatively dry climate, this region is characterised by convective thunderstorms and showers that usually occur in summer and early autumn months due to high temperatures and low-level instability (Llasat et al., 2016). The topographic conditions of the region favour these events. Warm and humid air masses coming from the sea reach the Catalan Coastal Range through convective motion, creating clouds that strongly discharge over the Tordera catchment (Urgell i Vidal, 2008). The response times of the catchments on the Catalan coast are usually short due the flood plains' urbanization and steep mountain slopes. As a result, this region is vulnerable to flash floods caused by heavy rainfall events (Alfieri et al., 2018). While summer convective events are usually short-lived, autumn events can be catastrophic due to the warmer sea surface temperature and organised perturbations (Llasat et al., 2016). As a consequence of such convective storms, most of the flash floods in Catalonia occur between August and October (Llasat, 2001). 35,1% of the Tordera river floods occur in October (Urgell i Vidal, 2008).

3.3 Data set description

3.3.1 Rainfall data from rain gauges

Although there is an extensive rain gauge network in Catalonia, there are only two active rain gauge stations within or close to the town of Blanes. The *Malgrat de Mar* station is an automatic station managed by the SMC (Meteorological Service of Catalonia), and the *Jardí Botànic* is managed by AEMET (Spanish Meteorological Agency). Table 3-1 describes the temporal resolution and the available time frames of data for both stations, and Figure 3-6 shows the location of both rain gauges within the study area. The rain gauges' historical data were used during the designing phase of the methodology, while real-time information is being used during the operational phase.

All the precipitation data provided by the SMC rain gauges go through post-measurement quality control. The quality management consists of a series of seven hierarchical and semi-automatic data verification processes: completeness control, range filter, control of temporal coherence, control of internal coherence, control of climatological coherence, control of spatial coherence and visual inspection. For example, the ranger filter is applied to detect extreme precipitation values that are impossible to occur in Catalonia according to its climatic conditions. The temporal and spatial coherence controls look for abrupt precipitation changes in time or space that could indicate measurement errors. The quality control is performed under the supervision of the SMC technical personnel, and once the data quality is assured, it can be stored in the database (METEOCAT, 2020a).

Table 3-1 Rain gauge stations metadata

Pluviometric Station	Available data	Temporal resolution
Malgrat de Mar (SMC)	2000-2013	mm/hour
	2014-2021	mm/30min
Jardí botànic Blanes (AEMET)	1969-2017	mm/day
	2018-2021	mm/hour

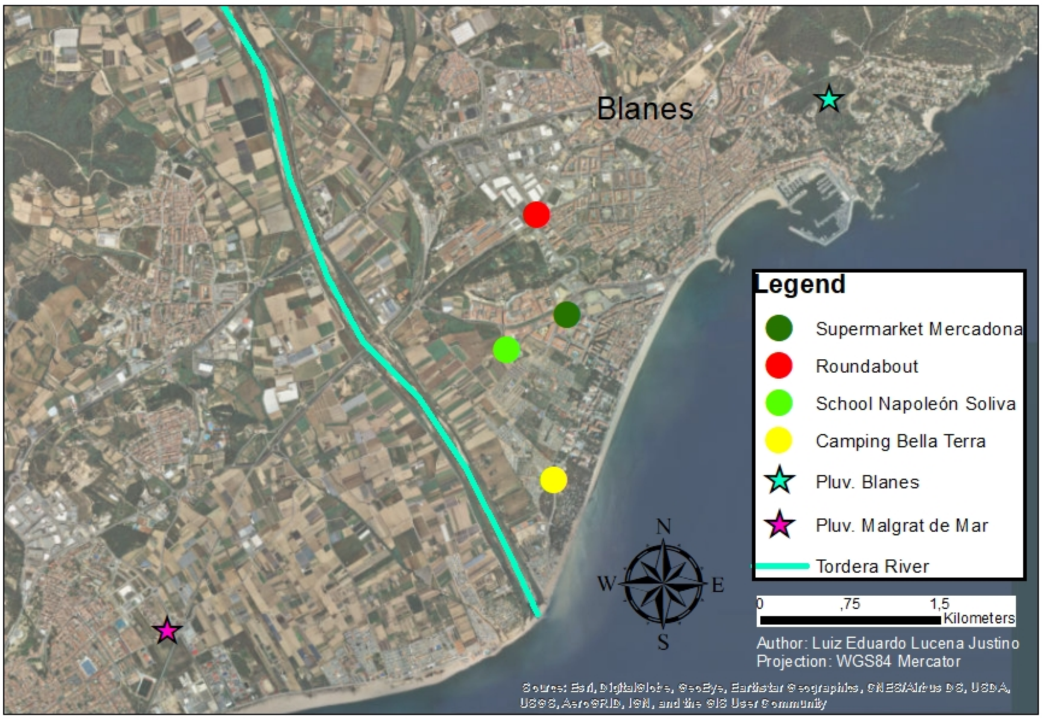


Figure 3-6 - Location of rain gauge stations

3.3.2 Weather radar data

The weather radar products data used in the operational phase of the SSEWS are provided by the SMC. The network known as XRAD (*Xarxa de Radars*) contains four integrated C-band Doppler weather radars (Figure 3-7). All radar observations from the SMC network go through correction processes to remove false radar echoes that could come, for example, from ground clutter and mountains. Furthermore, the Quantitative Precipitation Estimates (QPEs) generated by the XRAD are interpolated with observations from rain gauges for final estimations with improved quality (METEOCAT, 2021). The relatively dense network of radars – 4 radars for an area of approximately 32000 km^2 – was developed with the purpose of delivering high-quality QPEs in a region with such a complex topography as Catalonia. The XRAD performs scans every 6 minutes at short-range (130 km – 150 km) and long-range (250 km) (Rigo et al., 2010). The QPEs used in the operational phase of the SSEWS are short-range radar products and have a spatial resolution of 1 km x 1 km (Esbrí et al., 2021). Besides QPEs, Quantitative Precipitation Forecasts (QPFs) are generated by extrapolating radar observations using a nowcasting algorithm based on Lagrangian persistence (Berenguer et al., 2011).

Figure 3-7 - Location of Blanes and the four weather radars of the XRAD network. Adapted from: (Esbrí et al., 2021)

3.3.3 Numerical Weather Prediction (NWP) data

The Numerical Weather Prediction data used in the operational phase of the SSWES is obtained from the Integrated Forecasting System (IFS) model, managed by the European Centre for Medium-Range Weather Forecasts (ECMWF). The used data are forecasts of rainfall accumulations in the HRES (high resolution) configuration, which has lead times of up to 10 days, a spatial resolution of 9 km and 137 vertical levels. This configuration presents only one forecast member with no perturbations for the initial conditions. The IFS HRES performs 4 runs a day, at 00:00, 06:00, 12:00 and 18:00 (ECWMF, 2021). During the current operation of the SSEWS, a time window of just one day is being used.

3.4 Current practices for Early Warning Systems in the study area

There is currently an official multi-hazard EWS for weather-induced events in Catalonia, managed by the SMC. The Catalan EWS uses the approach of hazard-based thresholds. This system offers warnings for different types of weather-related hazards, such as rainfall accumulation, rainfall intensity, snowfall accumulation, wind, sea conditions and extreme temperatures.

Whenever a forecast indicates a hazard magnitude exceeding the predefined thresholds by the SMC for the coming three days, a warning called Dangerous Meteorological Situation is issued. The warnings levels are based on the expected degree of danger (*grau de perill*) and are classified into a traffic light code of four colours: green, yellow, orange and red. Such degree of danger is determined by the relationship of the threshold that can be exceeded and the hazard's probability of occurrence, and it varies on a scale from 1 to 6 (Table 3-2). The probabilities of occurrence are divided into the three following ranges: high probability (more than 70%), medium probability (between 30% and 70%) and low probability (less than 30%)

(METEOCAT, 2020b). The predefined thresholds for rainfall intensity and accumulation are presented in Table 3-3.

Table 3-2 - Likelihood-impact matrix used by the Catalan multi-hazard EWS. Source: Adapted from SMC, 2021

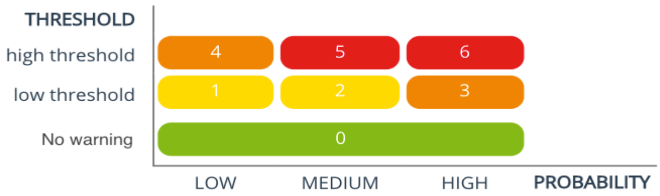


Table 3-3 - Predefined thresholds for Catalan EWS (rainfall intensity and accumulation). Source: SMC, 2021

Hazard	Low threshold	High threshold
Rainfall intensity	20 mm / 30 minutes	40 mm / 30 minutes
Rainfall accumulation	100 mm / 24 hours	200 mm / 24 hours

The warning levels (and their respective colours) are assigned to each *comarca* (administrative division equivalent to a county) in Catalonia. Daily, a report for each type of hazard is emitted with the following information: day of warning, time of issuance, a series of 4 maps (four intervals of 6 hours each) that indicates the expected warning levels in each *comarca*, the thresholds that are expected to be exceeded and a brief description of the hazard (SMC, 2021). Figure 3-8 presents an example of a warning for rainfall intensity issued by the Catalan EWS.

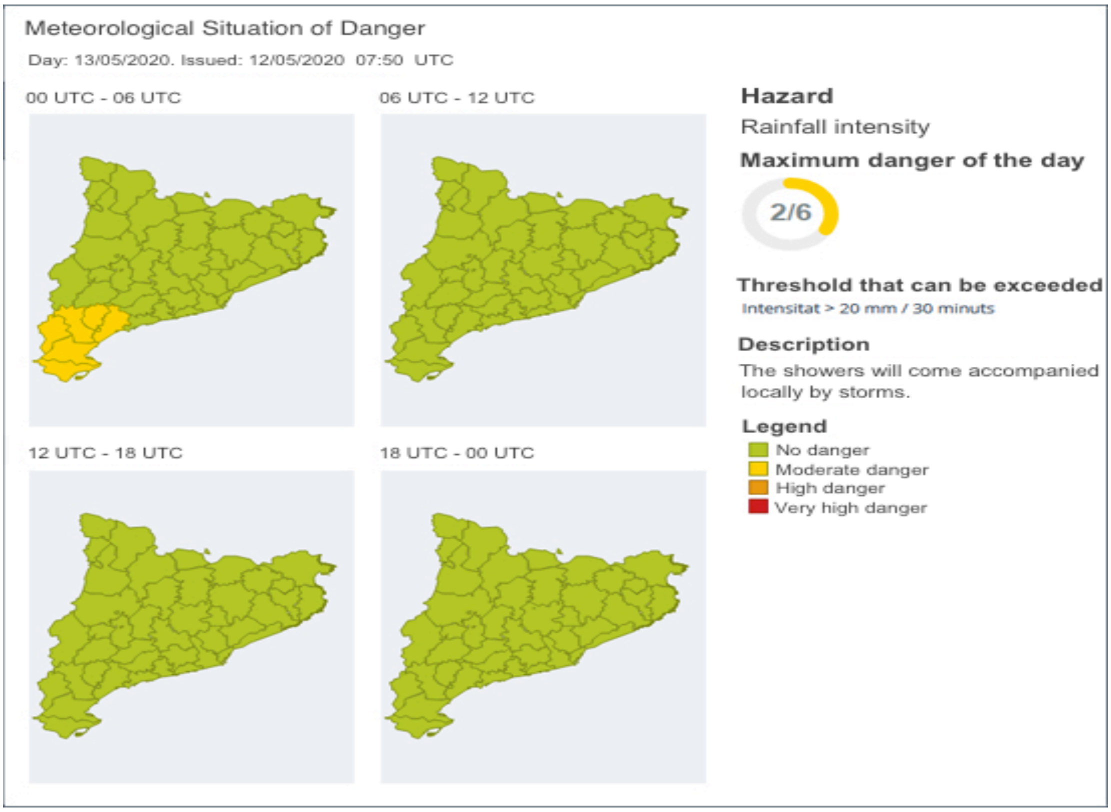


Figure 3-8 - Example of warning message of current Catalan EWS (rainfall intensity). Translated by the author. Source: METEOCAT (2020b)

CHAPTER 4

Methodology

This chapter presents the methodology used in this work. Initially, the main features of the novel SSEWS are explained. Then, the four main steps used to reach the research objectives are described in the following sections: data collection, design, implementation and evaluation. Each section describes the necessary tools and resources for the implementation of the respective methodology step.

4.1 Research approach

This work aimed to implement and evaluate a novel framework for site-specific impact-based flood warning systems. This framework (SSEWS hereafter) was designed by the Centre of Applied Research on Hydrometeorology from the Polytechnic University of Catalonia (Meléndez-Landaverde et al., 2021). During the writing of this thesis, the SSEWS was being parallelly evaluated in the municipality of Terrassa, Catalonia, Spain. In this work, the framework was transposed to a new study area and different types of specific sites. Therefore, this work can be described as a proof-of-concept (PoC), in which a particular method is performed so its feasibility and practical potential can be analysed (Kendig, 2015).

It is important to mention that the methodology used in this research blends steps obtained from the SSEWS framework with a validation exercise. Figure 4-2 presents a flowchart of the original SSEWS framework. Figure 4-2 presents a flowchart with the steps and sub-steps of the methodology used in this work.

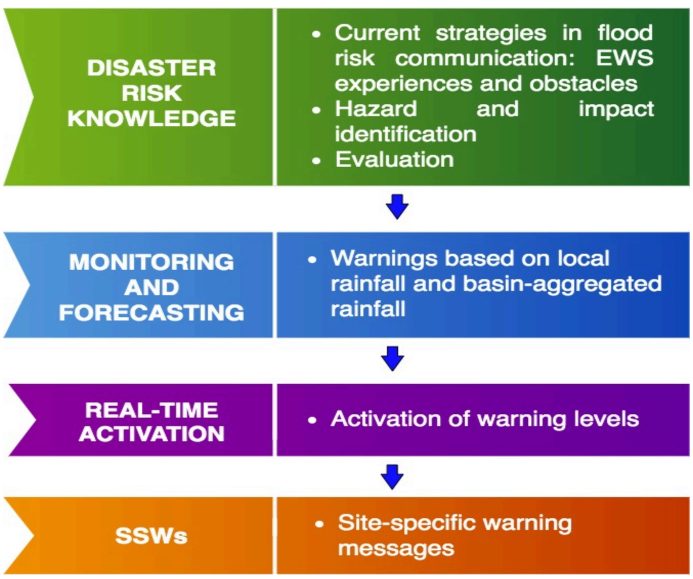


Figure 4-1 - SSEWS framework. Source: Meléndez-Landaverde et al. (2021)

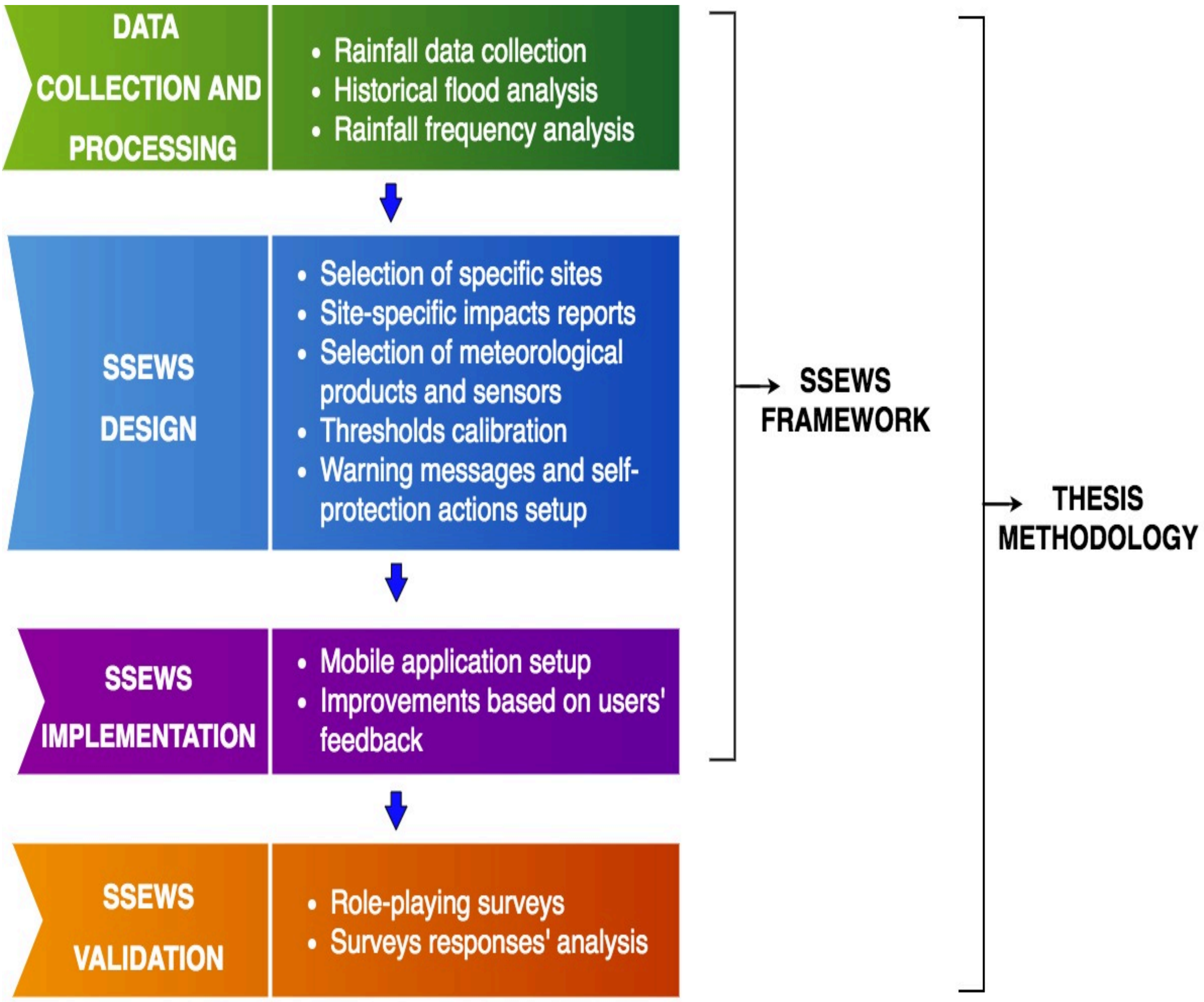


Figure 4-2 - Flowchart describing the research methodology

4.2 Site-specific Early Warning System (SSEWS)

The following paragraphs briefly describe the main concepts and features embedded in the proposed SSEWS.

Community-based approach

The SSEWS framework proposes that the design, implementation and operation of the EWS should be performed jointly with local stakeholders, including system end users. In the case study of this work, the system end users were the civil protection authorities and the citizens of Blanes. Therefore, the mentioned local stakeholders participated in all four main steps of the methodology of this work.

EWS for flash floods (pluvial and fluvial)

The proposed SSEWS is an EWS for urban (pluvial) and river (fluvial) flash floods (See section 2.4.1 Flash floods). Taking this into account, the EWS was tailored to the scale of both types of phenomena. The municipality of Blanes has a historical vulnerability for both kinds of floods.

Meteorological products

According to a review of the operational EWSs for water-related hazards in Europe, most of the European EWSs use NWP forecasts and river stage monitoring to trigger flood early warning systems (Alfieri et al., 2012). However, due to the inclusion of different types of flood phenomena with different spatial-temporal scales, the proposed SSWES uses different kinds of tools to trigger warnings: NWP-based forecasts, radar-based nowcasts and observations from rain gauges (See sections 3.3 Data set descriptionand 4.4.3 Selection of meteorological products and sensors).

EWS system based on impact-based rainfall thresholds

The most common approach for EWSs for urban (surface water) floods and river flash floods consists of rainfall thresholds-based systems. This approach involves comparing rainfall forecast values with reference thresholds, which are usually derived from statistical analysis of long-term point rainfall measurement data. Rainfall thresholds-based systems are indicated for flash urban or river floods because the processing time of hydrologic models or hydrodynamic urban flood models could compromise the possibility of issuing warnings with an appropriate lead time (Alfieri et al., 2012). Since the SSEWS has been mainly designed to cope with flash floods, it also uses an approach based on thresholds. Such thresholds can be either rainfall depths or their respective return periods. However, unlike most other rainfall thresholds-based systems, the SSEWS proposes calibrating thresholds based on a classification of impacts performed jointly with stakeholders such as civil protection authorities and system end users (See section 4.4.2).

Site-specific warning messages

The SSEWS framework suggests the use of early warning messages tailored to specific sites. To achieve that, it proposes the implementation of local flood vulnerabilities assessments during its designing stage. The framework suggests that it is more reasonable to gather vulnerability and exposure data, analyse impacts and propose recommendations for self-protection actions for specific sites. By delivering locally relevant information, the SSEWS aims at increasing end users' protective responses and flood risk awareness. Several authors suggested that it is appropriate to use local information in warning messages for localised phenomena, such as local flash floods (Mileti, 1995; Alfieri et al., 2012; Michoud et al., 2013; Cumiskey et al., 2015). In the study case of Blanes, the warning messages were designed for known flood vulnerable specific sites, such as a school and a camping site.

Impact-based warning messages

Besides calibrating thresholds based on past impacts, the SSEWS proposes warning messages that present a clear description of the expected impacts caused by a hazard (See section 2.3.2 Impact-based warnings Impact-based warnings can be produced subjectively, for example, by analysing the impacts caused by past events with stakeholders and experts, or objectively, by using complex impact models that incorporate vulnerability, exposure and meteorological data (WMO, 2015). The proposed SSEWS uses the first approach. In this case study, a research regarding past flood events in Blanes and their impacts was conducted to link expected impacts with impact-based rainfall thresholds.

Behavioural recommendations

Besides a clear description of the expected impacts during the disaster event, the proposed SSWES warning messages include self-protection actions that should be taken to mitigate the flood risk (See section 2.3.4 Warnings with behavioural recommendations In the study case, such behavioural recommendations were designed in accordance with the official local emergency management plans and current practices implemented by the local civil protection authorities.

4.3 Data collection and processing

4.3.1 Rainfall data collection and preparation

Due to the availability of rainfall data with finer temporal resolution and the proximity to the study area (See Table 3-1 and Figure 3-6), the rain gauge Malgrat de Mar was used to perform a rainfall frequency analysis of the region. Furthermore, the rain gauge had a long enough rainfall dataset (21 years) to perform a rainfall frequency analysis. Such analysis was a necessary step of the SSEWS framework because its results were later used to derive the reference impact-based rainfall thresholds.

The Malgrat de Mar rain gauge raw data was processed in order to extract rainfall annual maximum series, which were later necessary to perform a rainfall frequency analysis. The Pandas software library was used to process and organize the date. Pandas is a data manipulation software package written in the Python programming language. It is an open-source library that includes data structures and tools for manipulating structured data sets such as numerical tables and time series, which are common to several fields of sciences (Gilabert et al., 2009). Furthermore, Python was chosen as a programming language for data preparation due to its popularity and active community of users.

As it was already discussed, the SMC rainfall data go through post-measurement quality control that aims to correct possible measurement errors (See section 3.3.1). Therefore, the data presented no missing values. Moreover, no procedure for removing outliers was performed because the data quality was already controlled, and this could potentially remove real extreme events from the time series.

Annual maximum series were generated for four different rainfall accumulations: 30 minutes, 1 hour, 2 hours and 24 hours. Since there was no rainfall data for 30-minutes accumulation during 2000 – 2012, the hourly accumulated precipitation values were multiplied by a disaggregation factor of 2/3 during this period. For the 2 hours and 24 hours accumulations, a moving sum window was used to find the maximum accumulations in the time series.

4.3.2 Rainfall frequency analysis

The main objective of a rainfall frequency analysis is to relate the frequency of occurrence of extreme events to their magnitude using probability distributions. Therefore, such analyses indicate the frequency of occurrence to which a given rainfall event of a certain depth is equalled or exceeded. Since extreme events occur less frequently than moderate events, the frequency of occurrence of an extreme event is inversely related to its magnitude (Chow et al., 1988). The most commonly used approach for performing extreme value analyses is the Annual Maximum Series (AMS) method (Lang et al., 1999). Due to its simplicity, the AMS method was used in this work.

In hydrology, probabilistic distributions are typically used to summarise whole data sets into compact functions. The General Extreme Value (GEV) is a family of extreme values distributions developed under the extreme value theory that encompasses three limiting forms: Type 1 (Gumbel), Type 2 (Fréchet) and Type 3 (Weibull) (Chow et al., 1988). The Gumbel distribution is the most commonly used model for rainfall extremes (Koutsoyiannis, 2004). In this work, the annual maximum series were fitted to both the GEV general case (Equation 4-1) and the Gumbel distribution (Equation 4-2) through the Maximum Likelihood parameters estimation method (Chow et al., 1988). The Bayesian Information Criterion (BIC) and the Aikake Information Criterion (AIC) were used as quality indicators to select the best fitting distributions (Gilleland & Katz, 2016).

$$F(x) = \exp[-\left(1 - k\frac{x-u}{\alpha}\right)^{\frac{1}{k}}] \qquad \text{(Eq. 4-1)}$$

$$F(x) = \exp[-\exp(\frac{x-u}{\alpha})] \qquad \text{(Eq. 4-2)}$$

Where k, u and α are the parameters to be defined.

The extRemes package was used to fit the probabilistic distributions (function fevd) and to calculate the return periods (function return.level) for the four different rainfall accumulations: 30 minutes, 1 hour, 2 hours and 24 hours. The data length of the Annual Maximum Series for was 21 years for all the four rainfall accumulations. This was performed in RStudio, an Integrated Development Environment for the R programming language. Return periods of 2, 5, 10, 25, 50, 75, 100 and 250 years were generated with confidence intervals (function ci) of 95%. The extRemes package was used to its popularity within the weather and climate scientific communities in the context of extreme values analyses (Gilleland & Katz, 2016).

4.3.3 Historical flood analysis of Blanes

A historical flood analysis was performed to gather information about past flood incidents that took place in Blanes, as well as their respective impacts. The data was collected through two methods: semi-structured interviews (SSI) with the chief of the civil protection department of the city council of Blanes and a report derived from an online research. An SSI is a qualitative data collection method that consists of a two-way conversation. While an interview collects information using a series of predetermined questions, SSIs use a more conversational approach in which the participants explore the issues they consider relevant (Longhurst, 2003).

The report collected data from the following sources: online newspaper archives, blogs, social media, flood online databases and insurance companies' databases. The collected information was organised within a table containing impacts classified into several categories. The report included the insurance claim costs, the number of general insurance claims, the number of insurance vehicle claims, the taken mitigation measures, and the number of collected pictures and videos for each event. The report also included the maximum recorded rainfall accumulations (30 minutes, 1 hour, 2 hours and 24 hours) and their respective return periods. The followings tables present an example of the sections of the report containing the meteorological hazard data (Table 4-1) and impacts data (Table 4-2).

Table 4-1 - Example of flood report for the event of 15/08/2015 (meteorological hazard data section)

Event reference	8
Type	Pluvial
Date	15-Aug-15
Time (UTC)	14:30
Maximum 30-minutes-rainfall accumulation	31.2 mm
Return period for 30-minutes accumulation (years)	10<T<25
Maximum 1-hour rainfall accumulation	40.8 mm
Return period for 1-hour accumulation (years)	10<T<25
Maximum 2-hours-rainfall accumulation	41 mm
Return Period years for 2-hours accumulation (years)	2<T<5
Maximum 24-hours-rainfall accumulation	80.5 mm
Return period for 24-hours accumulation (years)	2<T<5

Table 4-2 - Example of flood report for the event of 15/08/2015 (Impacts section)

Short description	Floods in urban areas, roundabouts, four vehicles trapped in waters, fallen trees
Reported impacts	• “Ground floors, parking lots, commercial buildings and streets have been flooded in Blanes.” “The water entered the basements of several houses and commercial establishments, as well as in underground garages. One of the most problematic cases was the flooding that took place in a private car park for several vehicles, in a building located between Ibiza and Menorca streets, where the action of two fire brigades of the Generalitat was required. This is a car park of a block of neighbours that has already been flooded on previous occasions.” •“Severe floods occurred at the roundabout between Avinguda Europa and Carretera de Malgrat, where several vehicles were trapped on Friday and Saturday." "Several vehicles were trapped in this roundabout by the rapid rise of water that flooded the area. Four of them had to be removed with a crane assistance service, while the vast majority were able to leave on their own.” • “Another roundabout that was affected by the water was the junction of Avinguda Catalunya with Carrer Plantera, in the neighbourhood of the same name, although in this place no vehicle was trapped by the water.” •“The force of the water has washed away garbage containers and urban furniture.” “Fallen trees.” “In Blanes, approximately 2,700 have been left without electricity. ”
References	* https://www.blanesaldia.com/blanes/23838-icv-euia-proposa-una-bateria-de-mesures-per-evitar-noves-inundacions-a-blanes/ * https://www.blanesaldia.com/blanes/23819-policia-local-i-proteccio-civil-de-blanes-fan-mes-dun-centenar-intervencions-per-la-tempesta-dahir/ * https://www.lavanguardia.com/vida/20150815/54435837265/lluvias-tormentas-maresme-selva-valles-oriental.html * https://www.cuatro.com/noticias/sociedad/lluvias-Cataluna-inundaciones-coche-agua-granizo_2_2036505048.html * https://www.gerio.cat/noticia/212445/blanes-registra-50-litres-en-poc-mes-de-mitja-hora-inundant-carrers-i-baixos * https://twitter.com/nomixa/status/632228038281969665 *
Collected media	17 pictures and 3 videos
Insurance costs (euros)	182972.82
Insurance claims	60
Vehicle insurance claims	13
Damage to people	People got trapped into floodwaters at the roundabout at the junction of Av. Europa and Carretera Malgrat.
Damages to buildings	Houses, commercial buildings, basements and parking lots were flooded.
Disruption of transport/services	No reports.
Interruption of electricity	Approximately 2700 people experienced an interruption of electricity.
Damages to vehicles	Several vehicles were trapped at the roundabout at the junction of Av. Europa and Carretera Malgrat. 13 requests for vehicles insurance.
Affected specific sites	Av. Europa x Carretera Malgrat roundabout, Av. Plantera x Av. Catalunya roundabout and car parking between streets Ibiza and Menorca
Other damage	Fallen trees, flood waters washed away garbage containers and urban furniture.
Taken actions	The staff of the Blanes Local Police and Civil Protection carried out more than a hundred interventions of all kinds, with the support of the Generalitat Fire Brigade. Four vehicles trapped in floodwaters were removed with the assistance of a crane assistance service. Water was pumped from some basements and underground garages.

4.4 SSEWS design

4.4.1 Selection of specific sites

This step consisted of selecting specific sites in the municipality of Blanes at which the SSEWS should be implemented. The main criteria used in this task was selecting sites that have been historically affected by floods and still had significant flood vulnerability during the realization of this work. Since the SSEWS framework proposed a participatory codesigning approach, this step was performed jointly with the civil protection authorities from the city council of Blanes. The following sites were chosen: a roundabout, a kindergarten, a public primary school, a supermarket and a camping site. Figure 4-3 presents real pictures of the study case selected sites, and Figure 4-4 presents the location of the chosen specific sites within a flood map of Blanes. As shown in Figure 4-4, all the specific sites besides the roundabout are within the 10-years flood extension of the River Tordera, which justified the implementation of the SSEWS framework in such sites. The roundabout was identified in Blanes' historical flood analysis as being a site with recurrent severe impacts caused by urban flash floods.

Figure 4-3 - Specific sites: roundabout (1), primary school (2), supermarket (3) kindergarten (4) and camping site (5)

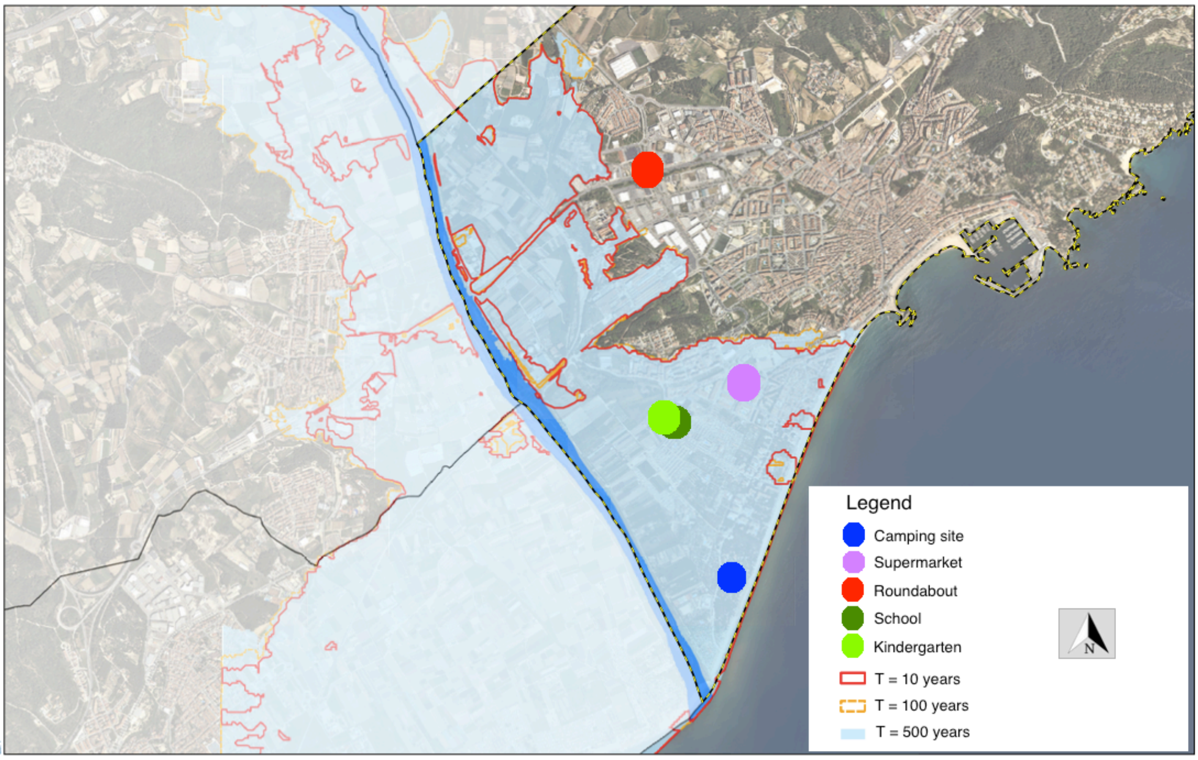


Figure 4-4 - Specific sites location within Blanes' flood map. Source: Adapted from Blanes (2016).

This section also consisted of selecting the SSEWS end users for each specific site. This was necessary because later, the warning messages and self-protection actions were tailored to the individuals who would receive the alerts. Table 4-3 shows the selected end users for the five chosen specific sites.

Table 4-3 - Selected end users for each specific site

Specific site	End users
School	Civil protection members, school management staff and teachers
Roundabout	Civil protection members, traffic authorities and first responders
Kindergarten	Civil protection members, kindergarten management staff and teachers
Supermarket	Civil protection members and supermarket management staff
Camping site	Civil protection members and camping site management staff

4.4.2 Site-specific impacts reports

After selecting vulnerable specific sites in Blanes, surveys were designed to collect data regarding impacts in the chosen sites. The main objective of such reports was to compile information about the effects caused by past intense rainfall events and the taken self-protection actions to mitigate such impacts. Moreover, such reports also aimed at collecting information about the perceptions of system end users regarding the current EWS for weather-related events in Catalonia (See section 3.4).

The surveys were designed and hosted on LimeSurvey, an open-source statistical survey web written in PHP. Since this task aimed to collect data regarding the local vulnerabilities to intense rainfall events, the SSEWS framework proposed that the survey respondents were people who potentially had experience with previous events in the specific sites. Therefore, two types of surveys were designed: one for the people who actively worked for emergency services in Blanes (first responders and civil protection staff) and another for citizens who worked at the specific sites. In both cases, the surveys had a similar structure. The following chart describes the surveys sections and summarises their main goals.

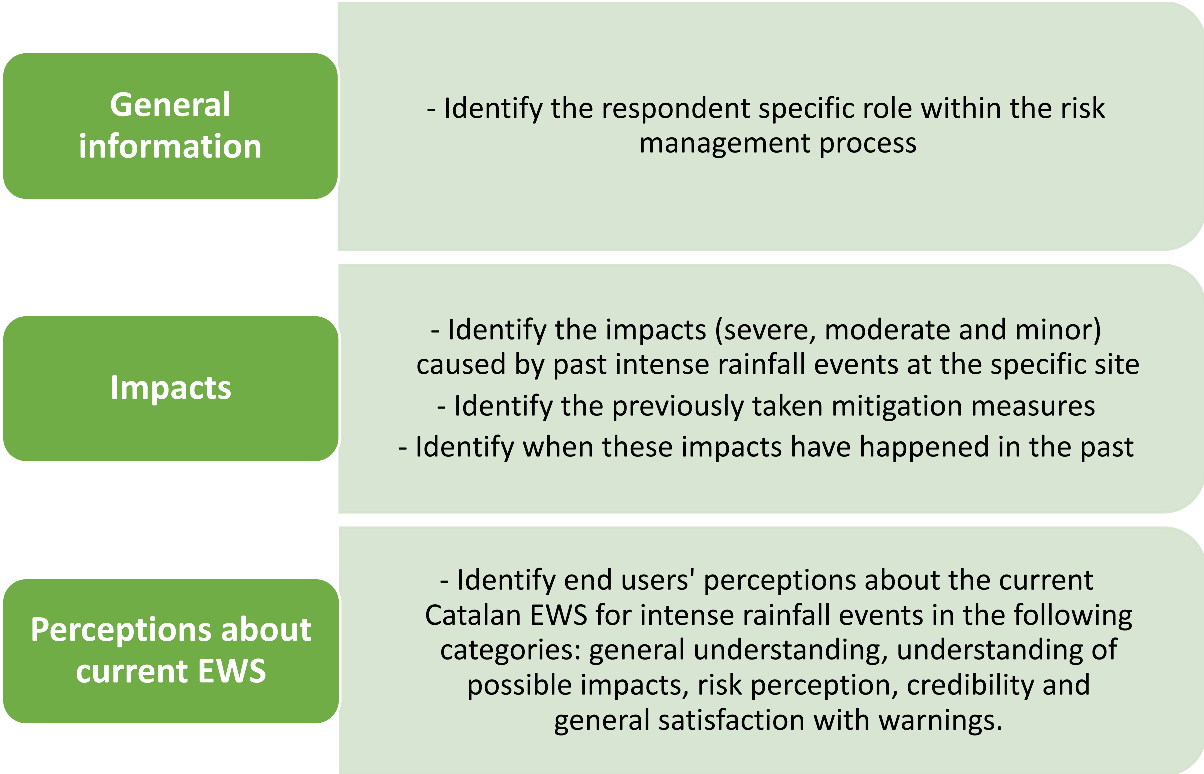


Figure 4-5 –Survey structure (components and their main objectives) for site-specific impacts reports

4.4.3 Selection of meteorological products and sensors

This step consisted of choosing which meteorological products and sensors would be used to trigger warnings during the operational phase of the SSEWS, as well as their configurations. The products and sensors were selected according to the availability of real-time data in the CRAHI-UPC servers. Table 4-4 presents the chosen products meteorological products and sensors, as well as their configuration for the SSEWS operational phase. For the weather radar and rain gauge data, 30-minutes rainfall accumulations were chosen because these periods are considered to be relevant at the point scale for urban flood events, and therefore, able to identity intense local rainfall events (Alfieri et al., 2015). For more information about the spatial and temporal resolutions of the chosen meteorological products, see section 3.3 Data set description).

Table 4-4 - Meteorological data used to trigger warnings during the SSEWS operational phase

Meteorological data		Units
Weather radar nowcasts and observations	Local rainfall accumulation (grid pixel)	(mm/30m)
	Basin-aggregated rainfall (FF-EWS)	T (return period)
Official alerts	Rainfall intensity alert	Level
	Rainfall accumulation alert	Level
NWP forecasts	Local rainfall accumulation (grid pixel)	(mm/24hrs)
	Local rainfall accumulation (grid pixel)	(mm/12hrs)
Rain gauge observations	Point rainfall accumulation	(mm/30m)

The flash-flood EWS (FF-EWS) was developed by the CRAHI-UPC and it is currently used by the Water Agency of Catalonia, in Spain (Corral et al., 2009; Corral et al., 2019). The FF-EWS is based on rainfall products generated by weather radars nowcasts and observations. It is equivalent to the ERICHA (European Rainfall-Induced Hazard Assessment System) flash-flood system and it assesses flash flood hazard by means of the exceeded return periods along a gridded drainage network (Ritter et al., 2020). However, while the FF-EWS uses input data from SMC radar network, the ERICHA system uses data from the OPERA radar composite (EFAS, 2021). Figure 4-6 presents the chain process of the ERICHA system. In these systems, the basin-aggregated rainfalls (i.e. the rainfall accumulated upstream of a drainage network point) and their respective return periods are used to describe the potential flash flood hazard level of a certain point of a drainage network of small and medium catchments. Such types of systems are indicated for catchments with a size of up to 2000 km^2 (Alfieri et al., 2015).

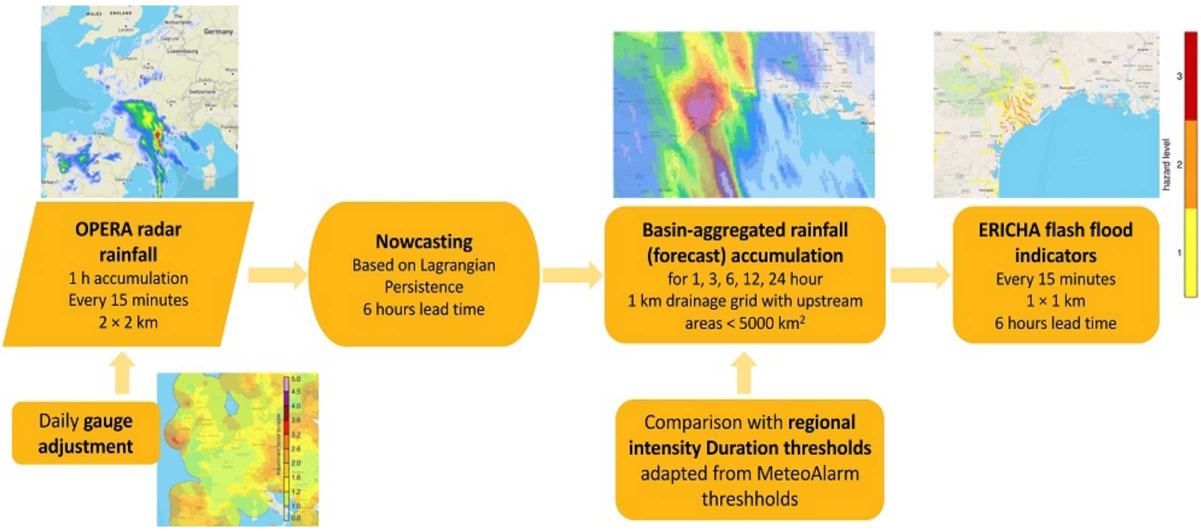


Figure 4-6 – ERICHA system chain process. Source: EFAS.

The aforementioned systems are based on the concept that flash flood hazard can be characterised by the basin-aggregated rainfall. This is primarily because in higher return periods, the probabilistic distribution functions (PDFs) of discharges tend to have a similar slope to the PDFs of rainfall (Guillot & Duband, 1967). The accumulated basin-aggregated rainfalls are calculated for periods of time corresponding to the basin-aggregated concentration times at each point of the drainage network. These systems do not consider relevant hydrological processes such as antecedent moisture conditions and snow melting. However, the lack of need to calibrate parameters justify their operational use by the EFAS (European Flood Awareness System) in detecting flash floods in small and medium catchments (Alfieri et al., 2015). The following table presents the specific sites' raster coordinates for the grid-based data used in the SSEWS, which included the weather radar-based and NWP-based data.

Table 4-5 – Specific sites' raster coordinates for grid-based data (weather radar and NWP)

Specific-sites	Return period of basin-aggregated rainfall (weather radar-based nowcast)		Local rainfall accumulation (weather radar-based nowcast)		Local rainfall accumulation (NWP-based forecast)	
	Row	Column	Row	Column	Row	Column
School	632	1107	234	325	19	33
	633	1107				
	632	1110	235	325		
	632	1111				
Roundabout	632	1107	235	325	19	33
	633	1107				
	633	1109				
	634	1109				
Camping site	626	1111	234	325	19	33
	627	1111				
Supermarket	632	1110	235	325	19	33
	632	1111				
	632	1113				
	632	1114				
Kindergarten	632	1107	234	325	19	33

4.4.4 Warning thresholds calibration

As previously mentioned, the SSEWS is an impact-based rainfall thresholds-based EWS (See section 4.2). The calibration of such thresholds was based on the previously collected data: historical flood analysis reports (See section 4.3.3) and return periods derived from the rainfall frequency analysis (See section 4.3.2). The rainfall thresholds were defined for 4 warning levels based on a traffic light colour code: green (no impacts), yellow (minor impacts), orange (moderate impacts) and red (severe impacts).

The SSEWS does not use rainfall-runoff models coupled with hydrodynamics models to determine flood hazard magnitude (flood depth, flood extent etc.). Instead, rainfall accumulations and return periods (hazard) were linked to site-specific impacts (vulnerability and exposure) caused by past flood events. For example, it could be observed from the historical flood analysis report that a rainfall accumulating over 28 mm/30 minutes was linked to severe impacts at the roundabout. Therefore, this was the threshold selected for the red warning level (severe impacts) for local rainfall accumulations in 30 minutes. This analysis was repeated for all the meteorological products and for all specific sites.

For urban floods, weather radar nowcasts (local rainfall accumulations), NWP forecasts (local rainfall accumulations), and rain gauge observations (point rainfall accumulation) thresholds were calibrated considering the past reported impacts. Since the weather radar nowcasts are more reliable in identifying convective intense rainfall events, the NWP forecasts data were assigned only to trigger the yellow level. For river floods, flash-flood hazard level thresholds were also calibrated based on the previous site-specific impacts. The official alerts from the current Catalan EWS for weather-related extreme events (See section 3.4) were also embedded on the SSEWS. The following table provides an example of the calibrated thresholds for the roundabout.

Table 4-6 - Example of calibrated thresholds for one of the specific sites (roundabout)

Meteorological product	**Data type**	**Yellow warning level threshold**	**Orange warning level threshold**	**Red warning level threshold**
Weather radar nowcasts	Local rainfall accumulation (mm/30min)	15	23	28
	FF-hazard level (return period in years)	T5	T10	T25
Official alerts	Rainfall intensity alert (level)	3	4	5
	Rainfall accumulation alert (level)	3	-	-
NWP forecasts	Rainfall accumulation (mm/12hours)	80	-	-
	Rainfall accumulation (mm/24hours)	42	-	-
Rain gauge observations	Rainfall accumulation (mm/30min)	15	23	28

4.4.5 Warning messages and self-protection actions

In this step, warning messages and self-protection actions to mitigate flood risk were defined for each warning level. For each specific site, warning messages were designed in accordance with the site's local vulnerabilities to contain a description of the expected impacts associated with the respective warning levels. Regarding the self-protection actions, the SSEWS framework proposed that they should be determined according to the existing site-specific Flood Emergency Response Plans (FERPs) and the current mitigation measures implemented by the local civil protection body (See section 4.4.2). In case the FERPs were not available, further information regarding self-protection actions could be obtained through SSIs with the local civil protection authorities, first responders, and relevant system end users from each specific site.

In all cases, the self-protection actions were tailored to SSEWS end users from each specific site. For example, the SSEWS end users of the primary school were its management staff and teachers. Therefore, the self-protection actions were defined as instructions that the primary school management staff and teachers could take to mitigate flood risk at the site. The yellow level self-protection actions were designed to give general advice to be alert to potential upcoming extreme rainfall-induced events. The orange warning level messages were designed to give instructions regarding preliminary actions that should be taken prior to an emergency. The red warning level gave instructions to act immediately (emergency level). Table 1 shows an example of the designed warning messages and self-protection action for the primary school.

Table 4-7 - Example of warning messages and self-protection actions for kindergarten

Warning level	Yellow	Orange	Red
Warning message	The possibility of an episode of heavy rain is forecast for the school. Although the weather conditions do not pose an immediate threat to this area, be aware as the weather can change rapidly and cause a possible interruption in the school activities. For more information about the protection actions you can take at the school, tap the actions icon.	An episode of heavy rain is forecast for the school area. Climatic conditions can cause floods in the playground area and low points of the school. Additionally, the rainy episode can cause urban flooding in the vicinity of the school. Take the indicated measures and follow the advice of the emergency services and local authorities. For more information about the protection actions you can take at the school, tap the actions icon.	A dangerous episode of heavy rain is forecast for the school area. Extreme weather conditions can cause significant floods in the playground and school's low areas. Additionally, the rain episode can cause severe urban flooding in the vicinity of the school. Take action immediately and follow the advice of emergency services and local authorities. For more information about the protection actions you can take at the school, tap the actions icon.
Self-protection actions	• Be alert to the evolution of weather conditions and the most recent rainfall forecasts • Check the school's self-protection plan and the actions to be taken in the event of an alert or emergency	• Review the school's self-protection plan • Keep students within the school • Suspend outdoor activities • Keep important documents in a high place	• Evacuate students from the school ground floor classrooms to the first-floor classrooms • In case an evacuation is requested from the neighbouring kindergarten, collaborate with the evacuation procedures

4.5 SSEWS implementation

4.5.1 Mobile application setup

The chosen interface to issue the SSEWS warning messages was the mobile application *Alertes Locals* (Catalan for local warnings). This app was designed by the CRAHI-UPC within the context of the ANYWHERE project, and it is currently available for iOS and Android mobile devices. The main features of the app are explained in the following paragraphs:

Map with specific-site icons: the application's main screen is composed of an interactive map with the location of the five specific sites. The map can be zoomed in and out, and the user can select which of the following 3 layers is shown: rainfall accumulation forecast by NWP (mm/hour), rainfall accumulation nowcast by weather radars network (mm/hour) and flash-flood hazard level (return period). A timeline bar at the bottom of the main screen allows the user to navigate through the weather radar observed rainfall accumulation in the last 90 minutes (mm/30 minutes), the weather radar nowcast for accumulated rainfall during the next 90 minutes (mm/30 minutes), and then the NWP forecast accumulated rainfall for the next 24 hours (mm/1 hour). The bar colour changes from green to yellow, orange or red when the forecast precipitation values exceed the predefined thresholds for any of the sites. Whenever a warning level is activated at a specific site, the site's icon colour also changes to the respective level colour. Figure 4-7 shows the app's main screen for the case where no warning is activated (green level).

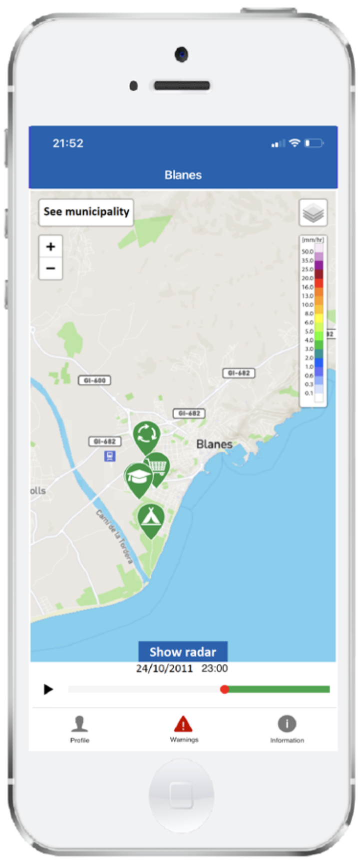


Figure 4-7 – Alertes Locals app main screen

Specific site general information, warning messages and self-protection actions: when the user taps one of the specific-sites icons in the app main screen (map), a page shows general information about the site containing the self-protection actions associated with all warning levels. In case a warning level is activated, this page shows the warning message and self-protection actions referent to this level. Figure 4-8 shows an example of the *Alertes Locals* app interface for a red level warning message at the kindergarten.

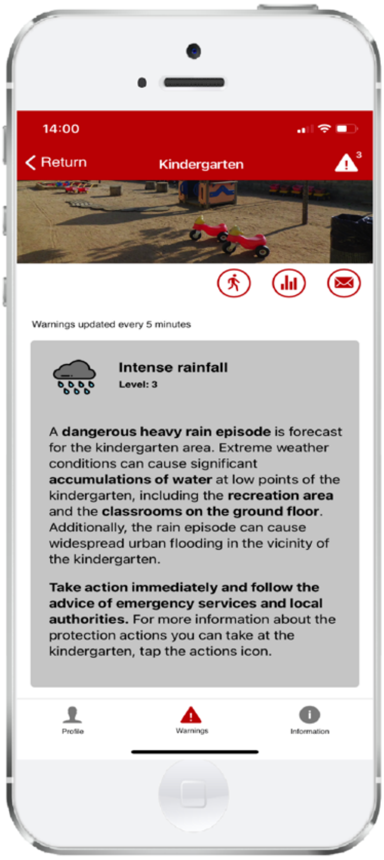


Figure 4-8 - Alertes Locals app warning message example (red warning level at kindergarten)

Push notifications: the app sends pop-up messages that can be visualised on the screen even if the user is not using the application when a warning message is received.

Information section: this section gives more detailed information about the types of warnings that can be received in the SSEWS, the map legend (colour bar) and the specific site icons.

4.6 SSEWS evaluation

4.6.1 Survey design

Although validation is a crucial element for EWSs, the SSEWS is a pilot framework for EWSs based on practices that are yet not well established, such as impact-based and site-specific warning messages. According to the WMO (2015) guidelines for impact-based forecast and warning services, validation of IFWSs should not only be based on an objective verification of warnings accuracy, but mainly on the evaluation of the overall system performance and usefulness. Furthermore, the SSEWS is based on a "people-centred" approach. Thus, the main objective of this validation exercise was to gather the system end users' perceptions regarding the proposed novel risk communication method.

During the initial phase of this thesis work, the SSEWS validation was proposed through two possible methods. Firstly, through a real-time test in case a significant rainfall event occurred after the SSEWS implementation. However, due to the climatic characteristics of the region, no significant rainfall event took place between the SSEWS implementation and the writing of this thesis. Secondly, through a live simulation exercise in which the system end users would be faced with a reproduction of an actual event, based on the WMO suggestions for validation of IBW services (WMO, 2015). However, due to the circumstances and restrictions for social contact (COVID-19 pandemic) during the course of this work, implementing such an exercise was not feasible.

As an alternative, an online survey was chosen as a method to collect the system end users' perceptions about the implemented SSEWS and the novel risk communication approach. The survey had a similar structure to the proposed live simulation exercise and used data from an actual past event. The conceptual design of this validation exercise was based on the following studies:

– *The influence of impact-based severe weather warnings on risk perceptions and intended protective actions* (S. H. Potter et al., 2018): this journal article compared impact-based warning messages to traditional hazard-based warning messages without impact information. An online survey was performed in which both types of warning messages were randomly assigned to the respondents in hypothetical scenarios of extreme weather events. The main goal of this study was to evaluate if introducing impact information into the warnings would increase the respondents' risk perception and their likelihood of taking protective actions.

– *Effects of impact-based warnings and behavioural recommendations for extreme weather events* (Weyrich et al., 2018): this journal article compared different types of warning messages that included impact information and behavioural recommendations into their content. An online survey based on a hypothetical scenario was also used in this study. The different types of warning messages were randomly assigned to the respondents, and the study aimed to analyse how each type of warning message affected the respondents' risk perception, warning understanding and intended behavioural responses.

- *112. Social: Design and evaluation of a mobile crisis app for bidirectional communication between emergency services and citizens* (Kaufhold et al., 2018): this study designed and evaluated an app based on a bidirectional communication approach between citizens and emergency authorities. The evaluation step used both live and paper-based simulations of the app. In the paper-based demonstration, the study used screenshots of the app to introduce the system to respondents and questions to analyse their perceptions about the app's technical features.

- *An interdisciplinary approach to Forecasting and Early Warning Systems* (Young et al., 2021): this section organised at the EGU 2021 General Assembly by the Water Youth Network, CRAHI-UPC and the University of Reading introduced a role-playing game in which participants had to make decisions in hypothetical weather-related emergency scenarios. The game presented different types of warning messages (impact-based or hazard-based) at different lead times. The event's main goal was to analyse if participants were more likely to take preventive actions if impact information was added to warning messages.

Several studies also used role-playing to evaluate EWSs' warning messages and people's decision-making process during weather-related emergencies (Radianti et al., 2017; Terti et al., 2017; Weyrich et al., 2021). Furthermore, other authors have shown that intended behavioural responses reactions to hypothetical flood warning scenarios could act an approximate proxy for actual intended responses during real events (Casteel, 2016; Ripberger et al., 2015). Therefore, the validation survey in this work also used a role-playing approach based on two hypothetical decision scenarios. Both scenarios used data from an intense rainfall event that took place in Blanes on the 24th of October 2011. In one of the scenarios, a warning message from the currently operational Catalan hazard-based early warning system (HBEWS) was shown to the respondents (See section 3.4). In another scenario, the SSEWS warning message was presented through a series of screenshots of the *Alertes Locals* app.

The survey was designed and hosted on LimeSurvey, which had necessary features for this exercise, such as randomization. Initially, the survey introduced a brief description of the study area and a set of instructions regarding the role the respondents had to play. Then, the two decision scenarios were presented with a randomly assigned order in order to reduce bias. In each scenario, a set of questions aimed at identifying the respondents' perceptions about both types of warning messages regarding the following aspects: understanding of warning message, understanding about possible impacts, risk perception, credibility, usefulness, and intended behavioural responses. Then, a section with a direct comparison of both systems was introduced. Finally, the last section collected personal information such as sex, age, educational level and past experiences with flood events. Figure 4-9 shows a chart that summarises the survey sections and their goals.

The survey was designed in Catalan for the SSEWS system end users, which included: local civil protection staff of Blanes, first responders of Blanes, and workers and clients from the specific sites. However, an English version of the survey was designed in order to collect perceptions from Flood Risk Management (FRM) experts from different countries. The English version of the survey can be found in the Appendix 1.

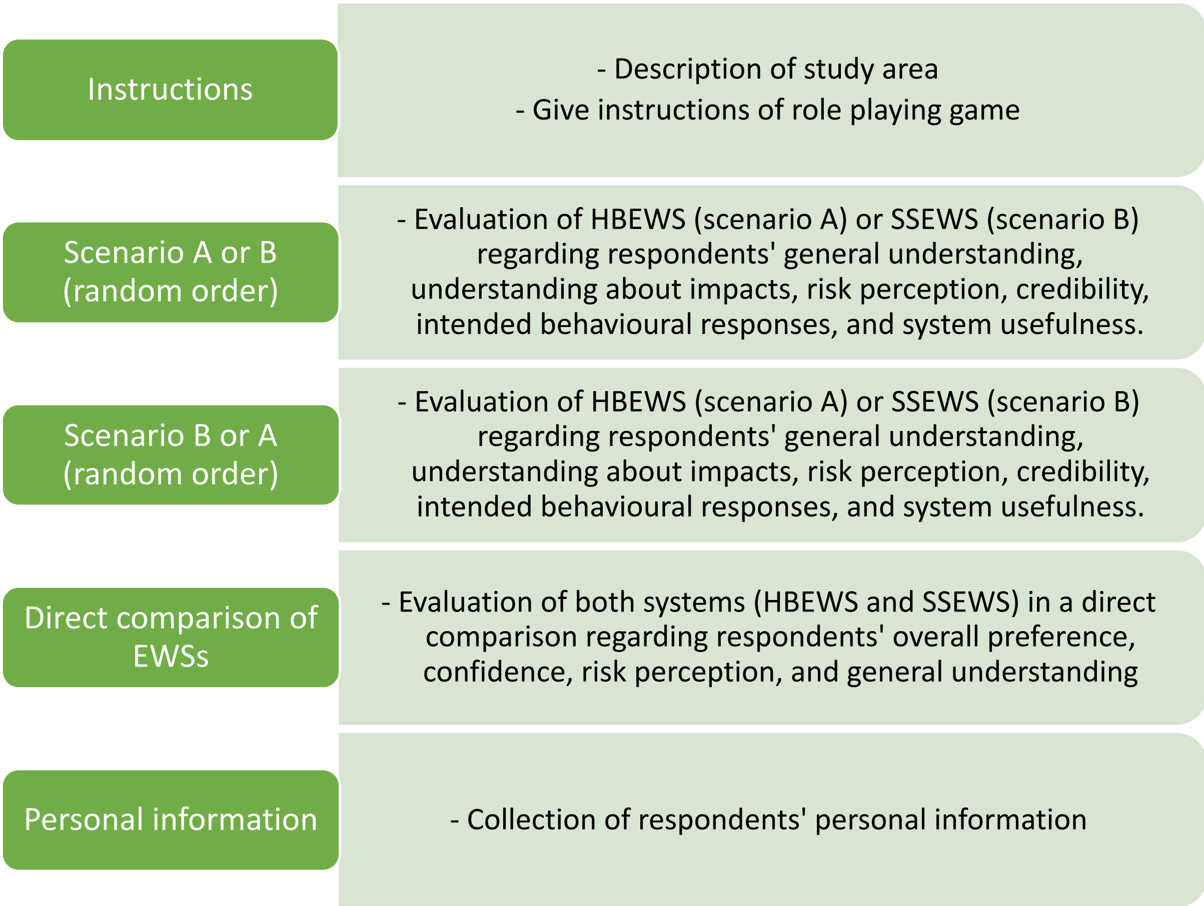


Figure 4-9 - Survey structure (sections and their objectives) for SSEWS validation

4.6.2 Survey responses statistical analysis

This study could be defined as a within-subjects study, in which the same group of individuals tested different conditions (performance of two EWSs) through the same set of dependent variables. The study consisted of one independent variable: the type of EWS (SSEWS or HBEWS). The dependents variables consisted of a series of warning perceptions attributes, potential intended behavioural responses and level of confidence regarding the intended behavioural response. Each dependent variable was linked to a single statement measured in an ordinal Likert scale ranging from 1 to 5 (strongly disagree, slightly disagree, neither agree nor disagree, slightly agree, and strongly agree). Table 4-8 presents the statements (dependent variables) used in this study.

Table 4-8 - Dependent variables (statements) of the study

Category	Statements
Warning perceptions	"The warning is easy to understand."
	"I find it easy to understand the possible impacts of the weather event at the kindergarten."
	"The warning makes me concerned for my safety and for the safety of children at the kindergarten."
	"Based on the warning, I understand the threats to my safety and the safety of other people at the kindergarten."
	"I believe the message to be credible."
	"Based on the warning, it is clear to me how I should modify my behaviour in case of a flood at the kindergarten, if necessary."
	"The warning message gives me enough information to take mitigation measures at my workplace."
	"I believe the message to be useful to my decision-making process in case of an emergency at the kindergarten."
Intended behavioural actions	"I would remain alert regarding the weather conditions, but would keep up with the school activities during the afternoon (2 p.m. to 6 p.m.)."
	"I would check out for other sources of information via my smartphone for confirmation or advice."
	"I would interrupt the school activities immediately (2 p.m.) and proceed with an evacuation for the children to a safer place."
Confidence	"I feel confident about the decisions taken."

Due to the aforementioned characteristics of the study, a Wilcoxon signed-rank test was used to evaluate the statistical significance of the median differences between paired observations of both EWSs. This test is a non-parametric equivalent of the paired-samples t-test and it requires three assumptions to be true. Firstly, the dependent variables have to be of the continuous or ordinal type. Secondly, the independent variable has to consist of matched pairs coming from the same population, such as in a study with two related groups with the same participants in each group. Finally, the Wilcoxon signed-rank test requires an approximately symmetrical distribution of differences of observations between the two related groups. If all conditions are met, the test can be implemented (Woolson, 2007).

The Wilcoxon signed-rank test contains a null hypothesis (H_0) that states that the median difference between paired values is equal to zero, and an alternative hypothesis (H_A) that states that the median difference between paired values is not equal to zero. The test statistic *p*-value indicates the probability of having results as extreme as the observed results in case the null hypothesis is assumed to be correct. If the test statistic *p*-value is small (<0.05), the null hypothesis can be rejected, and the test confirms that the median difference is different from zero with statistical significance. If p is greater than 0.05, the test indicates that there is no significant statistical difference between the medians of the two matched observed groups (Woolson, 2007). The statistical tests were performed on PSPP, a free software for the analysis of sampled data.

CHAPTER 5

Results and discussions

This chapter presents and discusses the results obtained from the implemented methodology. Initially, the results from the rainfall frequency analysis and municipality historical flood analysis are presented and discussed. Then, the calibrated thresholds for activating the SSEWS warning levels are reported. Finally, the last section presents the outcomes and discusses the findings from the SSEWS evaluation exercise.

5.1 Rainfall frequency analysis

The following tables present the results obtained from the rainfall frequency analysis performed to the rain gauge Malgrat de Mar annual maximum rainfall time series. Table 5-1 presents the AIC and BIC scores for both the GVE (general case) and Gumbel distributions, which were used to fit the annual maximum rainfall time series. The Gumbel distributions presented lower AIC and BIC scores in all rainfall accumulations (30-minutes, 1-hour, 2-hours and 24-hours). This means that the Gumbel distributions fit the extreme rainfall data better than the GEV (general case) distributions. Therefore, the return periods were derived from the Gumbel distributions.

Table 5-1 - AIC and BIC scores for GEV and Gumbel distributions

Rainfall accumulation period	Method	Distribution	AIC	BIC
30-minutes	Maximum Likelihood Estimation	GVE	137.4217	140.2550
		Gumbel	135.4818	137.3707
1 hour		GVE	162.4611	165.2944
		Gumbel	160.6959	162.5847
2 hours		GVE	162.4611	165.2944
		Gumbel	160.6959	162.5847
24 hours		GVE	190.4904	193.3237
		Gumbel	188.5095	190.3984

Table 5-2 presents the estimated return periods (2, 5, 10, 25, 50, 75, and 100 years) for the rainfall data from the rain gauge Malgrat de Mar, as well as their 95% confidence intervals. For all the rainfall accumulations, the return periods were derived from Gumbel distributions through the Maximum Likelihood parameters estimation method. Although the rain gauge was not located exactly at the same location of the chosen specific sites, it was considered to be close enough (distance ranging from 3 km to 4 km accordingly to the site) to characterise their approximate rainfall frequency characteristics.

Table 5-2 - Return periods for rainfall data (rain gauge Malgrat de Mar)

Rainfall accumulation	Return period (Years)	95% lower confidence bound (mm)	Estimate (mm)	95% higher confidence bound (mm)
30-minutes	2	12.3	16.2	20.1
	5	18.5	24.6	30.6
	10	27.0	30.1	37.9
	25	30.4	37.1	47.2
	50	33.7	42.3	54.2
	75	30.1	45.3	58.3
	100	31.4	47.5	61.2
1-hour	2	16.1	20.9	25.6
	5	23.6	31.1	38.6
	10	28.3	37.9	47.6
	25	33.9	46.5	59.1
	50	38.1	52.9	67.6
	75	40.5	56.6	72.6
	100	42.1	59.2	76.2
2-hours	2	23.0	29.5	36.1
	5	33.4	43.7	53.9
	10	39.8	53.0	66.2
	25	47.7	64.8	82.0
	50	53.4	73.6	93.8
	75	56.7	78.7	100.6
	100	59.1	82.3	105.5
24-hours	2	60.7	74.7	88.8
	5	83.4	104.9	126.4
	10	97.4	124.9	152.5
	25	114.6	150.2	185.9
	50	127.1	169.0	210.8
	75	134.4	179.8	225.3
	100	139.5	187.6	235.6

5.2 Municipality historical flood report and site-specific impacts reports

Table 5-3 describes the summary of the reported impacts (See section 4.3.3) in Blanes for 10 flood events that took place between 2005 and 2020. In order to fit this document page size, this table only shows the most relevant impacts for the events with impacts related to urban and river floods. Since the SSEWS was designed for urban and river floods, all events with impacts related to coastal floods were omitted from this report.

Table 5-3 - Summary of Blanes' historical flood impacts report

Type of event	Date	Time (UTC)	Summary of reported impacts
Urban flood	13-Oct-05	05:00	• Blocked access at highways GI-600, GI-661 and GI-681 • Two walls have fallen at the church of Blanes • Vehicles trapped on the roads due to local floods
Urban flood	24-Oct-11	04:00	• Floods in the city centre of Blanes (50 cm of water in some streets) • Floods in several commercial buildings and parking lots • Floods at Av. Europa • Train delays • Classes suspended at the kindergarten Can Borrell and primary school Pinya da Rosa • A four-story building had to be evacuated after cracks were detected in the structure • GI-600 road access was blocked • Power supply cut (3000 people)
Urban flood	30-Nov-14	17:00	• Floods in building basements, roofs, inner courtyards and streets • Floods at the intersection of Av. Europa and Av. L'Estació • Trapped car with two people at a roundabout (Av. Europa x Carretera Malgrat)
Urban flood	15-Aug-15	15:00	• Several vehicles trapped at a roundabout (Av. Europa x Carretera Malgrat) • Floods at roundabout (Av. Catalunya x Calle Plantera) • Power supply cut (2700 people)
Urban flood	13-Oct-16	18:30	• Power supply cut (519 people)
Urban flood	15-Nov-18	19:30	• Floods in several sites • Fallen trees • Landslides • Blocked access at some roads • Train circulation delays • Animals trapped in floodwaters (horses and dogs)
Urban flood	15-Oct-18	01:00	• Train line access blocked between Blanes and Maçanet de la Selva (fallen tree on the tracks) • Power supply cut
Urban flood	23-Oct-19	00:00	• Train line access blocked between Blanes and Maçanet de la Selva • Blocked road between Blanes y Calella
Urban flood/ River flood	22-Jan-20	01:00	• Two fallen bridges between Blanes and Malgrat de Mar • Roads closed • Floods in parking lots and basements • Floods in crop fields and campsites (La Tordera) • Floods in the city centre (Calle Ample: 20 centimetres water depth)
Urban flood	21-Apr-20	13:30	• GI-682 road access blocked in Blanes by landslides • Floods in basements • Fallen trees

The municipality historical flood report indicated which impacts were recurrent in the town of Blanes. During the analysed time, no deaths due to floods were reported. However, the report showed that potentially life-threatening impacts occurred in several events, such as floods in basements, underground parking lots and vehicles trapped in floodwaters. Furthermore, impacts related to infrastructural damage and interruption of services (e.g. transport systems, electricity) were reported in all events.

According to the historical report, most of the flood impacts in the town of Blanes (excluding coastal floods) were caused by urban flash floods resulting from intense localised rainfall events and not by river floods. The flood report also indicated that some specific sites in Blanes were especially vulnerable to urban floods. For example, severe floods were reported at the roundabout at the intersection of the Av. Europa and the Road Malgrat three times (2011, 2014 and 2015). Therefore, this roundabout was one of the selected specific sites for the SSEWS implementation (See section 4.4.2). Table 5-4 presents the maximum rainfall accumulation depths for the identified events in the historical flood report and their respective return periods.

Table 5-4 - Maximum rainfall accumulation depths and respective return periods for past flood events in Blanes

Date	**Maximum rainfall accumulation depths and respective return periods**							
	30 min. acc. (mm)	**TR**	**1 hour acc. (mm)**	**TR**	**2 hours acc. (mm)**	**TR**	**24 hours acc. (mm)**	**TR**
13-Oct-05	20	2<T<5	30	T<2	50	5<T<10	166.7	25<T<50
24-Oct-11	38.6	25<T<50	57.9	75<T<100	68.6	25<T<50	131.6	10<T<25
30-Nov-14	34.3	25<T<50	41.2	10<T<25	44.8	5<T<10	54.8	T<2
15-Aug-15	31.2	10<T<25	40.8	10<T<25	41	2<T<5	80.5	2<T<5
13-Oct-16	9.5	T<2	11.1	T<2	13.4	T<2	30.3	T<2
15-Nov-18	9.8	T<2	16.6	T<2	31.9	2<T<5	43.7	T<2
15-Oct-18	10.8	T<2	13.4	T<2	23.3	T<2	34.7	T<2
23-Oct-19	15.8	T<2	30.4	T<2	32.3	2<T<5	60.5	T<2
22-Jan-20	16.8	2<T<5	26.1	T<2	44.8	5<T<10	91	2<T<5
21-Apr-20	4	T<2	7.6	T<2	12.5	T<2	88.5	2<T<5

It could be observed from Tables 5-3 and 5-4 that there was a direct link between specific rainfall accumulation depths and the severity of certain impacts. For example, severe floods were reported at the roundabout between Av. Europa and Road Malgrat in the events of 24-Oct-2011, 30-Nov-2014 and 15-Aug-2015. Interestingly, these 3 events were associated with the 3 highest 30-minutes rainfall accumulations of the entire rainfall time series of rain gauge Malgrat de Mar (2000-2020). On the other hand, severe floods at the roundabout were not observed in other events with high 24-hours rainfall accumulations but relatively low 30-minutes rainfall accumulations, such as the events of 13-Oct-2005 and 22-Jan-2020. This indicates that severe floods at this roundabout were related to high-intensity rainfall events but not necessarily to high rainfall accumulations. Furthermore, the observed direct link between local rainfall depths and consequent urban flood impacts were aligned to the core concept of rainfall thresholds-based EWSs, which suggested that rainfall depths could be used as rough proxies of urban floods extents.

The historical flood analysis was also used to confirm and understand the severity of impacts in specific sites. For example, the report confirmed that the events of 2011, 2014 and 2015 were associated with the most severe floods that the roundabout has experienced during the analysed time (2005-2020). The report also indicated that such floods occurred due to a lack of capacity of the local drainage system, and the mitigation measures implemented by the local civil protection consisted of interrupting the traffic in the area and removing trapped vehicles with mobile cranes.

The municipality historical flood reports were also used to identify how local vulnerabilities varied over time. For example, the event in 2011 had the highest 30-minutes rainfall accumulation of all events. However, although severe floods were reported at the roundabout between Av. Europa and Road Malgrat, no vehicles were trapped in floodwaters at this specific site in the 2011 event. This is due to the fact that the peak of rainfall at this event occurred at 4:00 a.m. (UTC), when the traffic in the specific site was not significant. On the other hand, the peaks of rainfall in the events of 2014 and 2015 were recorded in the afternoon, at 5:00 p.m. and 3:00 p.m., respectively. Consequently, the roundabout experienced not only floods but also trapped vehicles into floodwaters in 2014 and 2015 (Figure 5-1).

Figure 5-1 – Urban floods at the roundabout between Av. Europa and Road Malgrat in 2014 and 2015. Source: (Blanesaldia.com, 2014; Carlos, 2015)

5.3 Warning activation rainfall thresholds

Table 5-5 presents the defined rainfall thresholds to trigger the yellow, orange and red warning levels. As mentioned before, the warning activation levels were defined for each site in accordance with the impacts reported in past events, the type of phenomena that could cause such impacts (urban or river flood), the types of meteorological products used to produce the forecasts and observations, and the site’s local vulnerabilities (See sections 4.4.3 and 4.4.4).

Table 5-5 – Defined rainfall thresholds to trigger SSEWS warning levels

Specific site	Warning level	Weather radar nowcasts		Official alerts		NWP forecasts		Malgrat de Mar rain gauge observations
		Local rainfall acc.	FF-hazard level	Rainfall intensity	Rainfall acc.	Local rainfall acc.	Local rainfall acc.	Point rainfall acc.
		(mm/ 30m)	Return period	Level	Level	(mm/ 24hrs)	(mm/ 12hrs)	(mm/30m)
Primary school	Red	34	T25	5	-	-	-	34
	Orange	28	T10	4	-	-	-	28
	Yellow	20	T5	3	3	80	42	20
Kindergarten	Red	28	T10	5	-	-	-	28
	Orange	23	T5	4	-	-	-	23
	Yellow	15	T2	3	3	50	27	15
Roundabout	Red	28	T25	5	-	-	-	28
	Orange	23	T10	4	-	-	-	23
	Yellow	15	T5	3	3	80	42	15
Camping site	Red	30	T25	5	-	-	-	30
	Orange	23	T10	4	-	-	-	23
	Yellow	15	T5	3	3	60	30	15
Supermarket	Red	34	T25	5	-	-	-	34
	Orange	28	T10	4	-	-	-	28
	Yellow	20	T5	3	3	50	27	20

5.4 SSEWS evaluation

This section describes and discusses the results obtained from the implemented validation survey.

5.4.1 Participants' general information

The validation survey was responded by a total of 61 people, which included 47 end users from the implemented SSEWS (group A) and 14 Flood Risk Management (FRM) experts (group B). The group of end users included the Blanes civil protection members, first responders and workers from the specific sites. Since the goal of this survey was to evaluate the SSEWS end users' perceptions regarding the proposed novel risk communication method, the analysed population consisted of the system end users (See Table 4-3). A larger sample size for the survey was not possible due to the limited amount of SSEWS end users. The group of FRM experts included both graduate students of the *Flood Risk Management* master and people who worked in Disaster Risk Reduction. Due do the nature of the study (matched-pairs design), an overall sample size of 61 respondents was considered to be sufficient. According to one of Roscoe's (1975) rules-of-thumb to define studies' sample sizes, simple experimental research consisting of tight controls (e.g. matched-pairs design) required samples as small as 10 to 20 respondents in order to be considered successful. According to Table 5-6 presents the participants' general information.

Overall, from the 61 survey respondents, 32 were male, 27 were female, and 1 person answered other gender. Most of the respondents had a higher education level. 28 people (45% of all respondents) had an undergraduate degree, and 19 people (31% of all respondents) had a postgraduate degree. From all participants, 29 people (54% of all respondents) had had previous experience with flood events, and 28 people (46% of all respondents) had never experienced a flood. The ratio of experience with previous flood events was significantly higher for the system end users (62%) than for the FRM experts (29%).

Table 5-6 – Survey respondents' general information

Parameter	Classification	N
Gender	Male	32 (A=27, B=5)
	Female	27 (A=20, B=7)
	Other	1 (B=1)
	Prefer not to say	1 (B=1)
Age	24 or less	1 (B=1)
	25 to 34	15 (A=4, B=11)
	35 to 44	11 (A=10, B=2)
	45 to 54	25 (A=25)
	55 to 64	8 (A=8)
	65 to 74	1 (A=1)
Education level	No school qualifications	1 (A=1)
	Secondary school	3 (A=3)
	Professional certificate	10 (A=10)
	Undergraduate degree (Bachelor's)	28 (A=20, B=8)
	Postgraduate degree (Master's or PhD)	19 (A=13, B=6)
Previous flood experience	Yes	33 (A=29, B=4)
	No	28 (A=18, B=10)
Survey language	Catalan	47 (A=47)
	English	14 (B=14)

5.4.2 Participants' perceptions of EWSs

This section presents the quantitative results from the evaluation survey regarding the system end users' (Group A, N = 47) and FRM experts' (Group B, N = 14) perceptions about two EWSs: the current Catalan hazard-based early warning system (HBEWS) for weather-related extreme events and the SSEWS proposed in this thesis work. A Wilcoxon signed-rank test was used to check if the difference in medians of paired dependent variables (statements about EWSs' perceptions) in the two observed groups (HBEWS and SSEWS) were statistically significant.

As previously discussed, a Wilcoxon signed-rank test requires an approximately symmetrical distribution of differences of observations between the two related groups (See section 4.6.2). For all the analysed 8 dependent variables, the histograms for distribution of the differences between the two paired observations in both groups presented an approximately symmetrical shape. Therefore, the Wilcoxon signed-rank could be used to analyse the data from the 8 dependent variables. As an example, Figures 5-2 presents the histogram for the distribution of the differences (SSEWS – HBEWS) for statement 1 ("The warning is **easy** to understand") in groups A (system end users).

Figure 5-2 - Histogram of distribution of differences of paired observations (Statement 1, Group A)

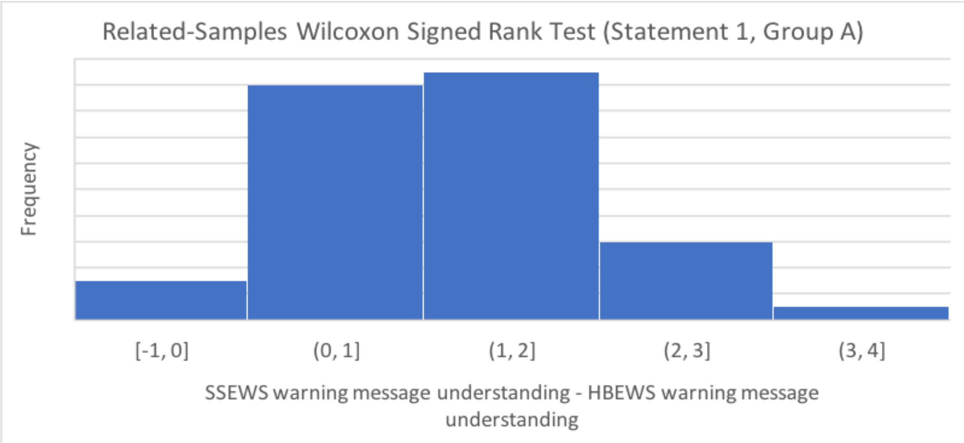


Table 5-7 presents the descriptive statistics for the 8 dependent variables for group A, including the test statistics for the Wilcoxon signed-rank test (CI=95%). Figure 5-3 presents a chart that contains the mean perceptions of system end users (group A). **The SSEWS performed better than the HBEWS in all the 8 analysed perception attributes for the system end users. Furthermore, the difference in medians of the two observed EWSs (HBEWS and SSEWS) were considered to be statistically significant for all 8 dependent variables.**

Table 5-7 - Descriptive statistics of 8 perception attributes regarding SSEWS and HBEWS (Group A: system end users)

Statement (perception attribute)	**HBEWS**		**SSEWS**		**Wilcoxon signed-rank test statistics**	
	Mean	**SD**	**Mean**	**SD**	***p***	**Z**
"The warning is **easy** to understand"	3.81	0.99	4.43	0.8	< 0.001	3.63
"I find it easy to understand the **possible impacts** of the weather event at the kindergarten"	3.32	1.24	4.34	0.7	< 0.001	4.5
"The warning makes me **concerned** for my safety and for the safety of children at the kindergarten"	3.53	1.06	4.38	0.74	< 0.001	4.94
"Based on the warning, I understand the **threats to my safety and the safety of other people** at the kindergarten"	3.28	1.16	4.45	0.75	< 0.001	5.13
"I believe the message to be **credible**"	3.85	0.88	4.19	0.8	0.024	2.25
"Based on the warning, it is clear to me how I should **modify my behaviour in case of a flood** at the kindergarten, if necessary"	3.23	1.07	4.32	0.73	< 0.001	4.56
"The warning message gives me **enough information** to take **mitigation measures** at my workplace"	2.74	1.13	4.17	0.79	< 0.001	4.99
"I believe the message to be **useful** to my **decision-making process** in case of an emergency at the kindergarten"	3.09	1.10	4.4	0.68	< 0.001	4.78

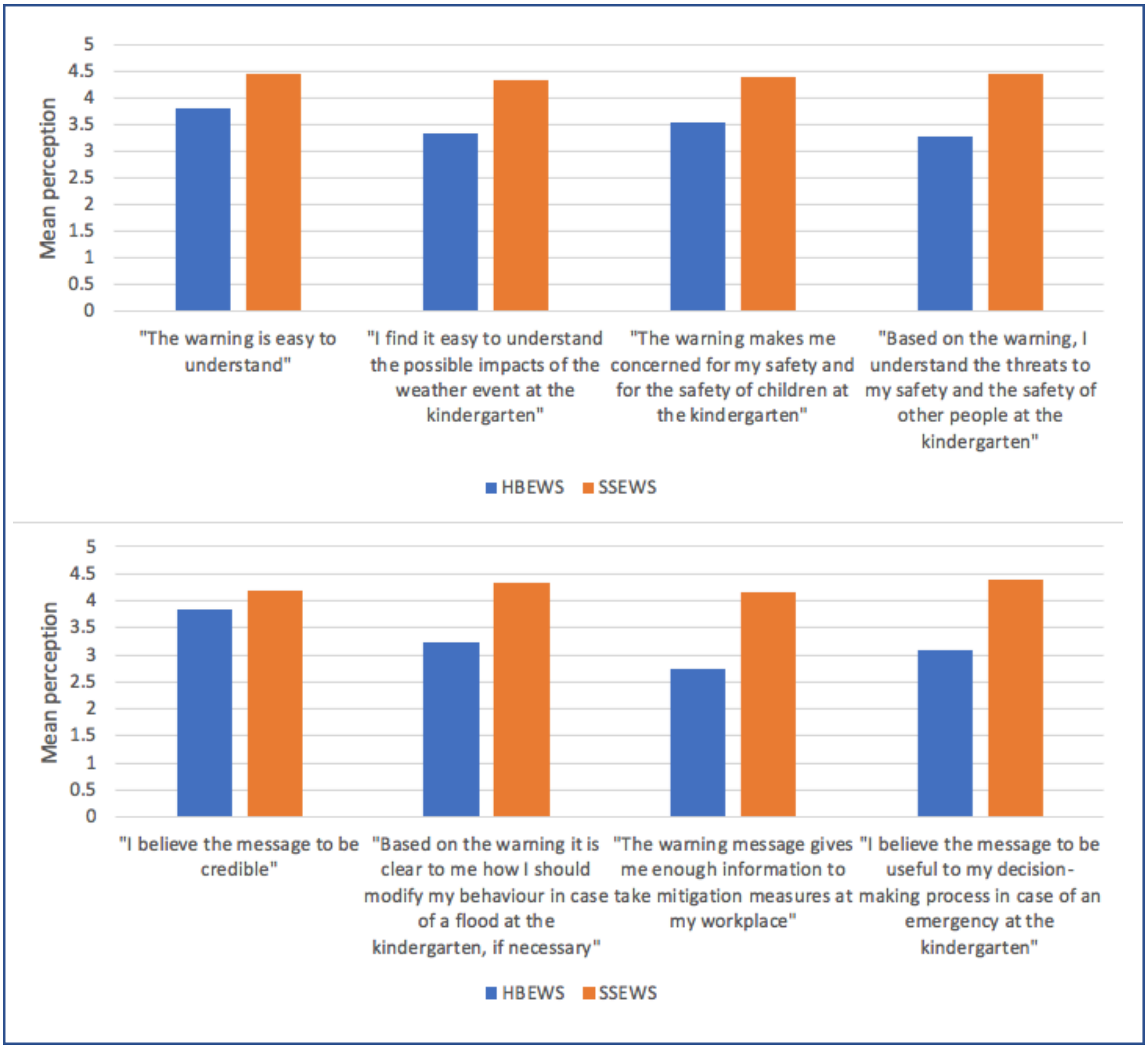


Figure 5-3 - Mean perceptions of warning information from system end users (Group A)

The table above indicates that the system end users found the SSEWS messages (M = 4.43, SD = 0.8, $p < 0.001$) to be easier to be understood than the HBEWS messages (M = 3.81, SD = 0.99, $p < 0.001$). The respondents also found it easier to understand the possible impacts of the extreme weather event at the specific site in the SSEWS (M = 4.34, SD = 0.7, $p < 0.001$) than in the HBEWS (M = 3.32, SD = 1.24, $p < 0.001$). Regarding the risk perception, the users found that the SSEWS warnings (M = 3.81, SD = 0.99, $p < 0.001$) made them more concerned for their safety and other people's safety than the HBEWS messages (M = 3.53, SD = 1.24, $p < 0.001$). Moreover, the users understood better the event's threats to their safety and to the safety of other people after receiving the SSEWS warning message (M = 4.45, SD = 0.75, $p < 0.001$) than after receiving the HBEWS message (M = 3.28, SD = 1.16, $p < 0.001$).

The survey respondents also found the SSEWS warning messages (M = 3.85, SD = 0.88) to be more credible than the HBEWS warning messages (M = 4.19, SD = 0.8). However, this was the perception attribute with the least significant statistical difference in all analysed statements ($p = 0.024$). Regarding the clarity of how to modify the behaviour in case of a flood, the system end users preferred the SSEWS warning messages (M = 4.32, SD = 0.73, $p < 0.001$) over the HBEWS (M = 3.23, SD = 1.07, $p < 0.001$). The SSEWS (M = 4.17, SD = 0.79, $p < 0.001$) also performed better than the HBEWS (M = 2.74, SD = 1.07, $p < 0.001$) regarding the provision of enough information to take mitigation measures in case of a flood event. Finally, the users found the SSEWS warning messages (M = 4.4, SD = 0.68, $p < 0.001$) to be more useful than the HBEWS warning messages (M = 3.09, SD = 1.1, $p < 0.001$) to their decision-making process during an emergency.

Table 5-8 presents the descriptive statistics for the 8 perception attributes for group B (FRM experts), including the test statistics for the Wilcoxon signed-rank test (Confidence interval = 95%). Figure 5-4 presents a chart that contains the mean perceptions of FRM experts (group B). **For the FRM experts, the SSEWS also performed better than the HBEWS in all of the 8 analysed perception attributes. The difference in medians of the two observed groups (HBEWS and SSEWS) were considered to be statistically significant in 6 out of 8 dependent variables.** Two perception attributes did not show relevant statistical difference ($p > 0.05$) between the two EWSs: facility to understand warning message ($p = 0.101$) and credibility ($p = 0.132$). This can be partially attributed to the relatively small sample size of group B (N=14), since the Wilcoxon signed-rank test statistic p tend to have higher values in tests performed to groups with smaller sample sizes.

Table 5-8 - Descriptive statistics of 8 perception attributes regarding SSEWS and HBEWS (Group B: FRM experts)

Statement (perception attribute)	HBEWS		SSEWS		Wilcoxon signed-rank test statistics	
	Mean	SD	Mean	SD	*p*	z
"The warning is **easy** to understand"	3.43	1.55	4.21	1.12	0.101	1.64
"I find it easy to understand **the possible impacts** of the weather event at the kindergarten"	2.36	1.50	4.29	0.83	0.006	2.77
"The warning makes me **concerned** for my safety and for the safety of children at the kindergarten"	3.36	1.22	4.43	1.16	0.007	2.72
"Based on the warning, I understand the **threats to my safety and the safety of other people** at the kindergarten"	2.93	1.54	4.36	0.93	0.007	2.69
"I believe the message to be **credible**"	3.57	1.22	4.07	1.21	0.132	1.51
"Based on the warning it is clear to me how I should **modify my behaviour in case of a flood** at the kindergarten, if necessary"	2.93	1.33	4.14	1.17	0.038	2.08
"The warning message gives me **enough information** to take **mitigation measures** at my workplace"	2.07	1.33	4.43	0.65	0.003	2.99
"I believe the message to be **useful** to my **decision-making process** in case of an emergency at the kindergarten"	3.50	1.56	4.43	0.94	0.015	2.43

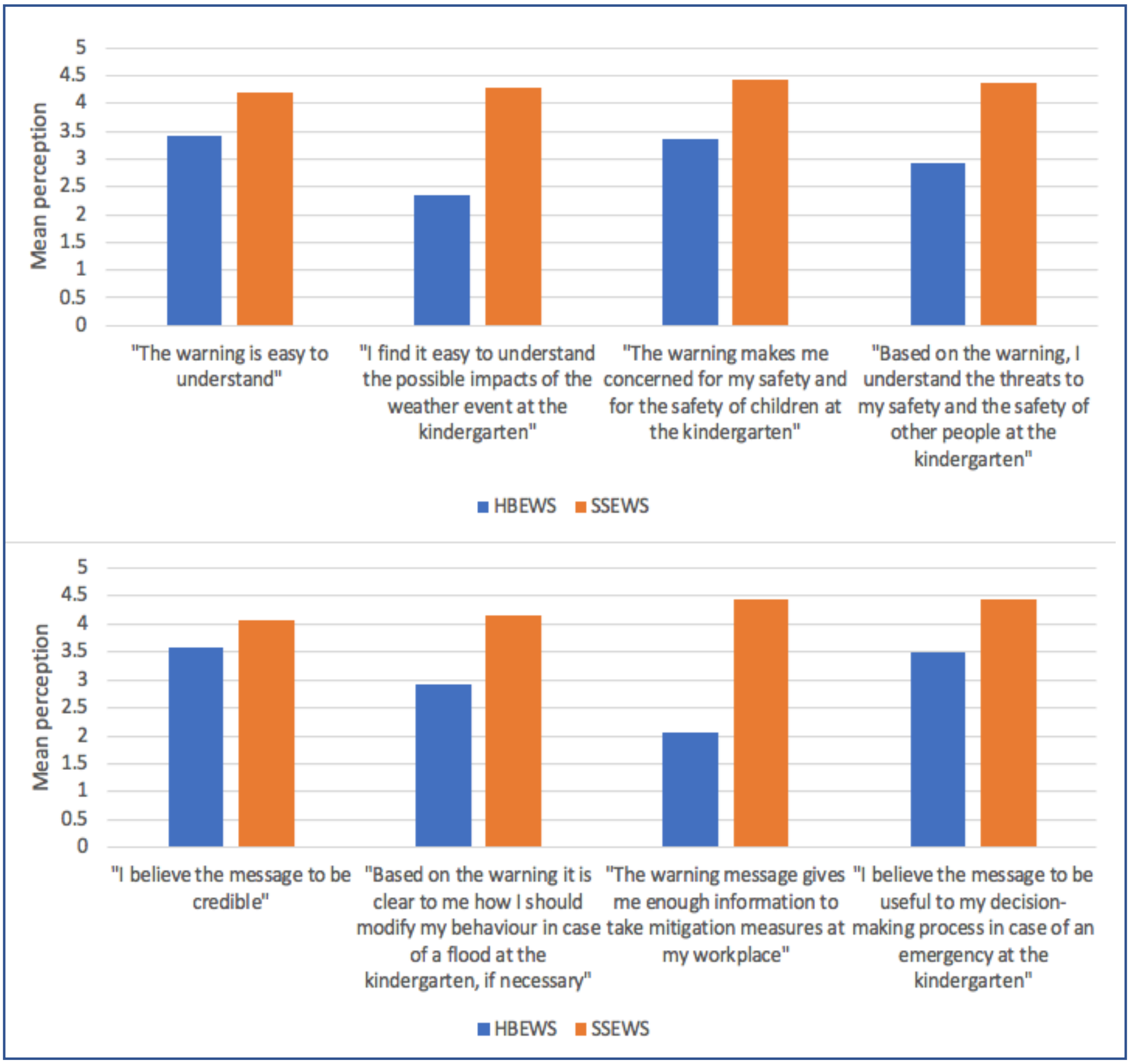


Figure 5-4 - Mean perceptions of warning information from FRM experts (Group B)

Table 5-9 describes the results from 5 questions which asked respondents to compare the two EWSs directly, with summed results from both groups A and B (N=61). In all the direct comparison questions, the SSEWS performed better than the HEBWS. 93% of the surveys' respondents stated that they preferred the SSEWS. 95% affirmed that the SSEWS made them feel more confident while making a decision. 92% would more likely recommend the SSEWS to a friend than the HBEWS. 90% indicated that the SSEWS warning messages were easier to understand. 95% stated the SSEWS made them more aware of the flood risk in the specific site.

Table 5-9 - Results from EWSs' comparison questions

Question	HBEWS	SSEWS
"Which system do you **prefer?"**	4 (7%)	57 (93%)
"Which system made you feel **more confident** while making a decision?"	3 (5%)	58 (95%)
"Which system would you more likely **recommend** to a friend?"	5 (8%)	56 (92%)
"Which system had warning messages that were **easier** to understand?"	6 (10%)	55 (90%)
"Which system made you more **aware** of the **flood risk** in the kindergarten?"	3 (5%)	58 (95%)

The results from this section were aligned to recent studies that suggested that including impact information and self-protection actions in the content of warning messages improved their general perception attributes. For example, Weyrich et al. (2018) found that the introduction of both impact information and behavioural recommendations in warning messages improved users' warning understanding, credibility perception, risk perception, threat understanding and understanding of how to respond to floods. Potter et al. (2018) suggested that including impact information into warning messages improved users' threat perception, concern and understanding of possible impacts.

However, it is important to note that the aforementioned studies analysed how individual factors (such as impact-based warning information and behavioural recommendations) improved warning messages' perceptions. This thesis work aimed to analyse how a whole novel framework for EWS with several features (site-specific warnings, impact-based information and behavioural recommendations) performed in comparison to an existent HBEWS. Still, the results confirm that a novel risk communication approach based on site-specific impact-based warnings coupled with behavioural recommendations produced an overal much higher satisfaction from users when compared to a traditional hazard-based warning service.

Other studies have also shown that general perception attributes were related to improvement in responses to warning messages. For example, Ripberger et al. (2015) has shown that the credibility of official warnings influenced warning responses. According to Sutton et al. (2018), fear and threat perception were shown to be influential elements in eliciting behavioural responses during disasters. Lazo et al. (2015) pointed out that several storm-related studies have revealed that perceived risk is also a major influence in deciding whether or not to take a protective response, such as an evacuation.

On the other hand, the observed improvements in risk perception and understanding levels in the SSEWS could be attributed to the length of the warning messages. Sutton et al. (2018) discovered, for example, that longer messages containing additional regarding local impacts and recommended self-protection actions were linked with improvements in message comprehension and faster intended responses. These findings suggest that authorities should ensure that early warning messages are easy to understand and that they should elicit feelings of concern. Furthermore, they should make sure that people understand potential threats to their safety. This could by supported by adding including additional impact information and behavioural recommendations into warning messages, as it was proposed by the SSEWS.

5.4.3 Participants' intended behavioural responses

Tables 5-10 (group A) and 5-11 (group B) present the descriptive statistics of the comparison of intended behavioural responses in the SSEWS and the HBEWS. Three statements were presented to the respondents containing potential flood risk mitigation measures that could be taken in the survey's hypothetical flood scenario. The respondents were asked about the likelihood of taking each of the presented actions. After that, they had to state how confident they felt in making the decisions. The intended responses included a strong risk mitigation behaviour (interrupt the school activities and proceed with an evacuation), a medium risk mitigation behaviour (check for advice from other sources of information), and a weak risk mitigation behaviour (remain alert but keep the school activities).

Table 5-10 - Descriptive statistics of intended behavioural responses in SSEWS and HBEWS (Group A: end users)

Statement (intended behavioural response or level of confidence)	HBEWS		SSEWS		Wilcoxon signed-rank test statistics	
	Mean	SD	Mean	SD	*p*	Z
I would **remain alert** regarding the weather conditions, but would keep up with the school activities during the afternoon (2 p.m. to 6 p.m.)	3.6	1.35	2.19	1.15	0.000	4.78
I would check out **for other sources of information** via my smartphone for confirmation or advice	4.26	0.90	3.89	0.94	0.032	0.85
I would **interrupt** the school activities immediately (2 p.m.) and proceed with an **evacuation** from the children to a safer place	2.55	1.35	3.87	1.1	0.000	4.56
I feel **confident** about the decisions taken.	3.36	1.01	3.96	0.72	0.000	3.49

For group A (system end users), the participants stated that they were more likely to take a weak risk mitigation measure (remain alert but keep the school activities) in the HBEWS (M=3.6, SD=1.35) than in the SSEWS (M=2.19, SD=1.15), with significant statistical difference ($p < 0.001$). The system end users were slightly more likely to take the medium risk mitigation behaviour (check for advice from other sources of information) in the HBEWS (M=4.26, SD=0.9) than in the SSEWS (M=3.89, SD=0.94), with significant statistical difference ($p = 0.032$).

On the other hand, the users indicated that they were more likely to take a strong risk mitigation measure (interrupt the school activities and proceed with an evacuation) in the SSEWS (M=3.87, SD=1.1) than in the HBEWS (M=2.55, SD=1.35), with significant statistical difference ($p < 0.001$). The users also stated that they felt more confident about their decisions in the SSEWS (M=3.96, SD=1.01) than in the HBEWS (M=3.36, SD=1.01), with significant statistical difference ($p < 0.001$). **Therefore, the survey results showed that the SSEWS warning message increased the system end users' likelihood to take a protective action, and it also increased their confidence while making the decision.**

Table 5-11 - Descriptive statistics of intended behavioural responses in SSEWS and HBEWS (Group A: FRM experts)

Statement (intended behavioural response or level of confidence)	HBEWS		SSEWS		Wilcoxon signed-rank test statistics	
	Mean	SD	Mean	SD	p	Z
I would **remain alert** regarding the weather conditions, but would keep up with the school activities during the afternoon (2 p.m. to 6 p.m.)	3.79	1.12	2.50	1.09	0.015	2.43
I would check out **for other sources of information** via my smartphone for confirmation or advice	4.29	0.73	4.00	0.96	0.395	0.85
I would **interrupt** the school activities immediately (2 p.m.) and proceed with an **evacuation** from the children to a safer place	2.50	0.94	4.21	0.97	0.004	2.9
I feel **confident** about the decisions made.	3.36	1.15	4.00	0.88	0.111	1.59

Some past studies also indicated that implementing both impact information and behavioural recommendations into warning messages increased the likelihood of people taking protective actions. For example, Meléndez-Landaverde et al. (2020) found that warning messages containing impact information triggered more protective responses than hazard-based warning messages. Casteel (2016) found the adding both impact information and behavioural recommendations into warning messages produced higher likelihoods of taking a protective response. Ripberger et al. (2015) also found that introducing a description of impacts in warning messages made people more likely to take a protective action.

However, no studies that analysed the influence of site-specific warnings in intended behavioural responses were found. Since this feature was not analysed individually, the aforementioned results could not confirm that the use of site-specific warnings without impact information and behavioural recommendations would have improved the users' intended protective actions. Nonetheless, the findings of this study support that presenting both site-specific impact-based warnings and behavioural recommendations simultaneously has substantial benefits in terms of increasing risk perception, comprehension of warnings, and intended behavioural responses. These findings provide factual support for the additional cost and efforts associated with the adoption of such practices into EWSs.

CHAPTER 6

Conclusions and recommendations

This chapter presents this work's findings for each of the previously proposed research questions. The limitations of the study and recommendations for future research are subsequently discussed.

6.1 Research conclusions

Research question 1: Is it feasible to implement a novel framework for site-specific impact-based flood early warnings in Blanes, Spain?

- This research supported the development and evaluation of a novel framework for a site-specific impact-based flood EWS, named here SSEWS. The successful transposal of the SSEWS framework to a new case study location (Blanes, Spain) helped to confirm its feasibility and practical potential.

Research question 2: What are the requirements for transposing a novel framework for site-specific impact-based flood early warnings to other sites?

- The implementation of the proposed SSEWS requires collaboration from local key stakeholders, which include the local emergency management staff (civil protection authorities and first responders) and system end users. In this work, the participation of stakeholders from Blanes was essential during the assessment of local flood vulnerabilities, selection of the EWS activation rules and definition of self-protection actions.

- The SSEWS design phase requires access to rainfall measurement past data records from the location, which could be either from rain gauges or remote sensing products. In this work, point rainfall measurements records were used to analyse the regional frequency of extreme events and to characterise depths of past extreme events in the study case location.

- The operational phase of the SSEWS requires real-time weather forecasting services from both weather radar networks and NWP models, as well as real-time data from rainfall and/or river gauge monitoring stations. It also requires an IT infrastructure and servers' management service to store and provide data.

- The operational phase of the SSEWS needs a periodical reassessment of warning activation rules, warning messages contents, and proposed mitigation actions, since flood vulnerability and exposure are highly dynamic in time and space.

Research question 3: What were the main impacts of past urban and river flood events in Blanes?

- The assessment of Blanes' flood vulnerability indicated that most impacts caused by floods in the town were associated with urban floods, which were typically a consequence of short and localised intense convective storms. The town has also been shown to be vulnerable to impacts caused by river floods, but with a lower frequency.

- The city has recurrently experienced the following potentially life-threatening urban floods impacts: vehicles trapped in floodwaters, flooding of basements and underground parking lots. It also experienced infrastructural damages and interruption of services due to intense rainfall events several times in the past 15 years.

- The neighbourhoods *La Plantera, Els Pins* and *Estació* were characterised as the town's most vulnerable areas to both urban and river floods. The regions around *Avinguda Europa* were found to be especially vulnerable. Five flood-prone specific sites in these neighbourhoods were selected for the implementation of the SSEWS: a primary school, a kindergarten, a roundabout, a supermarket and a camping site.

Research question 4: Does a novel site-specific impact-based flood warning service improve Blanes citizens' warning perceptions when compared to a traditional hazard-based warning service?

- This study analysed the Blanes citizens' warning perceptions regarding the following attributes: understanding of warning messages, understanding of possible flood impacts, understanding on how to respond to a flood event, risk perception, usefulness of warning and credibility. The novel SSEWS has been shown to improve all warning perceptions when compared to the current hazard-based warning service used in Catalonia, with statistical significance in all analysed attributes.

- A further evaluation was implemented to analyse the same warning perceptions in a group of Flood Risk Management experts from other countries. For this group, the novel SSEWS has also been shown to improve all the warning perceptions. However, no statistical significance was found in the attributes of understanding of warning messages and credibility.

Research question 5: Does a novel site-specific impact-based flood warning service improve Blanes citizens' intended protective actions when compared to a traditional hazard-based warning service?

- The novel SSEWS has shown to statistically improve Blanes citizens' intended protective actions in a hypothetical flood scenario based on a real event. In an evaluation done to FRM experts, the SSEWS has also been shown to statistically improve their intended protective actions in the same hypothetical flood scenario.

6.2 Research limitations

The findings of this work have to be cautiously considered within the context of the following limitations:

- The proposed SSEWS framework was implemented in Spain, an advanced economy. 70% of the system end users who answered the evaluation survey said they had a higher education degree. Since the SSEWS framework advocates for a user-oriented approach, this methodology would likely have to be adapted if implemented in other economically vulnerable regions of the world. For example, warning messages could include voice alerts in regions with lower literacy rates. Other dissemination pathways such as siren alarms or flags could be used instead of a mobile application in regions with less access to mobile services.

- Due to the limited time span of this thesis work, the EWSs' evaluation was done through an online survey with a hypothetical flood scenario, which was designed with data from a real event. Despite the fact that intended actions in hypothetical scenarios can be used as rough proxies of real responses in emergencies, a performance evaluation based on real events would offer more meaningful insights into the weaknesses and strengths of the proposed risk communication method.

- The proposed SSEWS risk communication approach consisted of delivering site-specific information, a description of potential impacts and behavioural recommendations. Although the SSEWS has been shown to improve both people's warning perceptions and intended protective responses, this research did not evaluate on an individual basis which features of the proposed framework were responsible for such improvements.

- In addition to analysing warning perceptions and intended protection actions from EWS end users, this work reproduced the evaluation instrument to a group of FRM experts. The outcome from the evaluation performed in the two groups cannot be directly compared due to different samples size and different degrees of knowledge regarding the site's local vulnerabilities.

- The SSEWS proposes the use of two hydrometeorological products for the generation of river floods warnings: a flash-flood hazard level indicator or river stage data. Due to the small size of the catchments in the case study location and its local climatic characteristics, only the flash-flood hazard level indicator was used to account for river floods. It is noteworthy that this indicator is only recommended for flash floods in small and medium catchments of up to 2000 km^2. This work did not consider forecasting services for river floods phenomena with large spatial and temporal scales. Forecasting river floods with better lead times in larger catchments would require the use of rainfall-runoff modelling, which is not encompassed by the SSEWS framework.

6.3 Recommendations for future research

- Up to now, the SSEWS framework has been implemented in two towns in Catalonia. Both cities have very similar socioeconomic and hydrometeorological characteristics. Future research could transpose the framework to regions with different socioeconomic and/or hydrometeorological characteristics. In any case, the SSEWS framework would have to be tailored to the users of the new study case location and to its particular vulnerabilities. Furthermore, implementation in different types of specific sites could be explored.

- This research has proposed the use of tailored impact-based site-specific warnings for a flood-prone urban area. The SSEWS operational phase uses forecasting services derived from weather radar networks, NWP models, and also rain gauge or river gauge observations. Future research could include forecasting services derived from hydrological rainfall-runoff modelling in the SSEWS framework, since these services offer a better lead time for river floods taking place on larger spatial and temporal scales.

- This study evaluated the performance of a novel flood EWS, which proposed the use of user-oriented site-specific warnings. Future research could evaluate the performance of this framework with the addition of a temporal component. In this case, the rainfall thresholds would be calibrated considering how flood vulnerability changes in time. For example, the proposed rainfall thresholds would have higher values during periods of a site's higher vulnerability, such as the summer season in a camping site or the rush traffic hour in a road section.

- The evaluation component of this work focused on analysing a new communication risk approach, consisting of site-specific flood warnings with possible impacts and recommended self-protection actions. The proposed SSWES dissemination pathway for warnings was a mobile application. Future research could evaluate not only the risk communication approach but also the technical features of the mobile application. These features could include the app's design, handling, usability, connectivity issues and stability.

References

ACA. (2017). *La gestió del risc d'inundacions a Catalunya* (pp. 1–34).

AEMET. (2020). *Borrasca Gloria*. http://www.aemet.es/es/conocermas/borrascas/2019-2020/estudios_e_impactos/gloria

Albayrak, T., Caber, M., Rosario González-Rodríguez, M., & Aksu, A. (2018). Analysis of destination competitiveness by IPA and IPCA methods: The case of Costa Brava, Spain against Antalya, Turkey. *Tourism Management Perspectives*, *28*(June), 53–61. https://doi.org/10.1016/j.tmp.2018.07.005

Alfieri, L., Berenguer, M., Knechtl, V., Liechti, K., Sempere-torres, D., & Zappa, M. (2018). Handbook of Hydrometeorological Ensemble Forecasting. In *Handbook of Hydrometeorological Ensemble Forecasting* (Issue January). https://doi.org/10.1007/978-3-642-40457-3

Alfieri, L., Salamon, P., Pappenberger, F., Wetterhall, F., & Thielen, J. (2012). Operational early warning systems for water-related hazards in Europe. *Environmental Science and Policy*, *21*, 35–49. https://doi.org/10.1016/j.envsci.2012.01.008

ANYWHERE Project. (2021). http://anywhere-h2020.eu/

Basher, R. (2006). *Global early warning systems for natural hazards: systematic and people-centred. Philosophical transactions of the royal society a: mathematical, physical and engineering sciences, 364(1845), 2167-2182.*

Berenguer, M., Sempere-Torres, D., & Pegram, G. G. S. (2011). SBMcast - An ensemble nowcasting technique to assess the uncertainty in rainfall forecasts by Lagrangian extrapolation. *Journal of Hydrology*, *404*(3–4), 226–240. https://doi.org/10.1016/j.jhydrol.2011.04.033

Blanes, Ajuntament de. (2016). *Estudi de inundabilitat. Revisió del Poum de Blanes. Avanç de pla*.

Blanes, Ayuntamiento de. (2008). *Pla d'ordenació urbanística municipal de Blanes: Memòria.* 421.

Blanesaldia.com. (2014, December 1). *Cap incidència greu a Blanes a conseqüència de la llevantada i la plujae*. https://www.blanesaldia.com/blanes/19803-cap-incidencia-greu-a-blanes-a-consequencia-de-la-llevantada-i-la-pluja/

Carlos. (2015). *Un muerto al hundirse el porche de su casa por la lluvia en la garriga*. http://ea3ean.blogspot.com/2015/08/un-muerto-al-hundirse-el-porche-de-su.html

Casteel, M. A. (2016). Communicating increased risk: An empirical investigation of the National Weather Service's impact-based warnings. *Weather, Climate, and Society*, *8*(3), 219–232.

Casteel, M. A. (2018). An empirical assessment of impact based tornado warnings on shelter in place decisions. *International Journal of Disaster Risk Reduction*, *30*, 25–33.

Chaturvedi, P., Srivastava, S., & Kaur, P. B. (2017). Landslide early warning system development using statistical analysis of sensors' data at Tangni landslide, Uttarakhand, India. *Proceedings of Sixth International Conference on Soft Computing for Problem Solving*, 259–270.

Chow, V. Te, Maidment, D. R., Mays, L. W., & Ven Te Chow, David R. Maidment, L. W. M. (1988). *Applied Hydrology* (pp. 1–294). http://ponce.sdsu.edu/Applied_Hydrology_Chow_1988.pdf

Cornwall, W. (2021). *Europe's deadly floods leave scientists stunned*. American Association for the Advancement of Science.

Corral, C, Velasco, D., Forcadell, D., Sempere-Torres, D., & Velasco, E. (2009). *Advances in radar-based flood warning systems. The EHIMI system and the experience in the Besòs flash-flood pilot basin*.

Corral, Carles, Berenguer, M., Sempere-Torres, D., Poletti, L., Silvestro, F., & Rebora, N. (2019). Comparison of two early warning systems for regional flash flood hazard forecasting. *Journal of Hydrology*, *572*, 603–619.

Cumiskey, L., Werner, M., Meijer, K., Fakhruddin, S. H. M., & Hassan, A. (2015). Improving the social performance of flash flood early warnings using mobile services. *International Journal of Disaster Resilience in the Built Environment*.

ECWMF. (2021). *Operational configurations of the ECMWF Integrated Forecasting System (IFS)*. https://www.ecmwf.int/en/forecasts/documentation-and-support

EFAS. (n.d.). *Flash flood indicators*. Retrieved June 3, 2021, from https://www.efas.eu/en/flash-flood-indicators

Esbrí, L., Rigo, T., Llasat, M. C., & Aznar, B. (2021). Identifying Storm Hotspots and the Most Unsettled Areas in Barcelona by Analysing Significant Rainfall Episodes from 2013 to 2018. *Water*, *13*(13), 1730. https://doi.org/10.3390/w13131730

EUMETNET. (2021). *Meteoalarm*. https://meteoalarm.org/en/page/about

Fakhruddin, S. H. M., Kawasaki, A., & Babel, M. S. (2015). Community responses to flood early warning system: Case study in Kaijuri Union, Bangladesh. *International Journal of Disaster Risk Reduction*, *14*, 323–331.

France24.com. (2021). Germany questions warning system after deadly floods. *France24*.

Frewer, L. (2004). The public and effective risk communication. *Toxicology Letters*, *149*(1–3), 391–397.

Georgakakos, K. P. (1986). On the design of national, real-time warning systems with capability for site-specific, flash- flood forecasts. *Bulletin - American Meteorological Society*, *67*(10), 1233–1239. https://doi.org/10.1175/1520-

0477(1986)067<1233:OTDONR>2.0.CO;2

GFDRR, G. F. for D. R. R. and R. (2016). *Implementing Multi-hazard Impact-based Forecast and Warning Services*.

Gian, Q. A., Tran, D.-T., Nguyen, D. C., Nhu, V. H., & Tien Bui, D. (2017). Design and implementation of site-specific rainfall-induced landslide early warning and monitoring system: a case study at Nam Dan landslide (Vietnam). *Geomatics, Natural Hazards and Risk*, *8*(2), 1978–1996.

Gilabert, P. L., Gadringer, M. E., Montoro, G., Mayer, M. L., Silveira, D. D., Bertran, E., & Magerl, G. (2009). An efficient combination of digital predistortion and ofdm clipping for power amplifiers. *International Journal of RF and Microwave Computer-Aided Engineering*, *19*(5), 583–591. https://doi.org/10.1002/mmce.20381

Gilleland, E., & Katz, R. W. (2016). ExtRemes 2.0: An extreme value analysis package in R. *Journal of Statistical Software*, *72*(8). https://doi.org/10.18637/jss.v072.i08

Guillot, P., & Duband, D. (1967). The Gradex to compute extreme flood probability from the observation rainfall. *International Hydrology Symposium*, *1*, 506–515.

Harrowsmith, M. (2015). *A case study series published by the UNISDR Scientific and Technical Advisory Group*. *December 2011*. www.metoffice.gov.uk/public/weather/warnings/?regionName=uk

Instituto de Estadística de Cataluña, . (2021). *Blanes (Selva), El municipio en cifras.* idescat.cat/emex/?id=170237&lang=es

Kaltenberger, R., Schaffhauser, A., & Staudinger, M. (2020). “What the weather will do” – results of a survey on impact-oriented and impact-based warnings in European NMHSs. *Advances in Science and Research*, *17*, 29–38. https://doi.org/10.5194/asr-17-29-2020

Kaufhold, M. A., Rupp, N., Reuter, C., Amelunxen, C., & Cristaldi, M. (2018). 112.Social: Design and evaluation of a mobile crisis app for bidirectional communication between emergency services and citizens. *26th European Conference on Information Systems: Beyond Digitization - Facets of Socio-Technical Change, ECIS 2018*.

Kendig, C. E. (2015). What is Proof of Concept Research and how does it Generate Epistemic and Ethical Categories for Future Scientific Practice? *Science and Engineering Ethics*.

Koutsoyiannis, D. (2004). Statistics of extremes and estimation of extreme rainfall: II. Empirical investigation of long rainfall records. *Hydrological Sciences Journal*, *49*(4), 591–610. https://doi.org/10.1623/hysj.49.4.591.54424

Landaverde, E., Sempere-Torres, D., & Berenguer, M. (2020). Towards impact-based communication during emergencies: Development of site-specific warning services in Catalonia. *EGU General Assembly Conference Abstracts*, 1011.

Lang, M., Ouarda, T. B. M. J., & Bobée, B. (1999). Towards operational guidelines for over-threshold modeling. *Journal of Hydrology*, *225*(3–4), 103–117.

https://doi.org/10.1016/S0022-1694(99)00167-5

Lazo, J. K., Bostrom, A., Morss, R. E., Demuth, J. L., & Lazrus, H. (2015). Factors affecting hurricane evacuation intentions. *Risk Analysis*, *35*(10), 1837–1857.

Llasat, María Carmen. (2001). An objective classification of rainfall events on the basis of their convective features: Application to rainfall intensity in the Northeast of Spain. *International Journal of Climatology*, *21*(11), 1385–1400. https://doi.org/10.1002/joc.692

Llasat, Maria Carmen, Marcos, R., Turco, M., Gilabert, J., & Llasat-Botija, M. (2016). Trends in flash flood events versus convective precipitation in the Mediterranean region: The case of Catalonia. *Journal of Hydrology*, *541*(September 2002), 24–37. https://doi.org/10.1016/j.jhydrol.2016.05.040

Longhurst, R. (2003). Semi-structured interviews and focus groups. *Key Methods in Geography*, *3*(2), 143–156.

Macherera, M., & Chimbari, M. J. (2016). A review of studies on community based early warning systems. *Jàmbá: Journal of Disaster Risk Studies*, *8*(1).

Marchezini, V., Trajber, R., Olivato, D., Munoz, V. A., de Oliveira Pereira, F., & Luz, A. E. O. (2017). Participatory early warning systems: youth, citizen science, and intergenerational dialogues on disaster risk reduction in Brazil. *International Journal of Disaster Risk Science*, *8*(4), 390–401.

Matas Hidalgo, E. (2013). (2013). *Disseny d'un parc urbà sostenible per a Blanes.*

Meiyan, J., Lianchun, S., Tong, J., Di, Z., & Jianqing, Z. (2015). China's implementation of impact and risk-based early warning. *Boletín-Organización Meteorológica Mundial*, *64*(2), 11–14.

Meléndez-Landaverde, E. R., Werner, M., & Verkade, J. (2020). Exploring protective decision-making in the context of impact-based flood warnings. *Journal of Flood Risk Management*, *13*(1). https://doi.org/10.1111/jfr3.12587

Meléndez-Landaverde, E., Sempere-Torres, D., & Berenguer, M. (2021). A people-centred approach for emergency communication: The case of site-specific warnings in Terrassa, Spain. *EGU General Assembly Conference Abstracts*, EGU21-12638.

Meléndez-Landaverde, E. R., Werner, M., & Verkade, J. (2020). Exploring protective decision-making in the context of impact-based flood warnings. *Journal of Flood Risk Management*, *13*(1), e12587.

METEOCAT. (2020a). *Control de qualitat de dades de les EMA*. https://www.meteo.cat/wpweb/divulgacio/equipaments-meteorologics/estacions-meteorologiques-automatiques/control-de-qualitat-ema/

METEOCAT. (2020b). *Situació Meteorològica de Perill*. https://www.meteo.cat/wpweb/divulgacio/la-prediccio-meteorologica/situacio-meteorologica-de-perill/

METEOCAT. (2021). *La Xarxa de Radars del Servei Meteorològic de Catalunya (XRAD)tle*.

Michoud, C., Bazin, S., Blikra, L. H., Derron, M. H., & Jaboyedoff, M. (2013). Experiences from site-specific landslide early warning systems. *Natural Hazards and Earth System Sciences*, *13*(10), 2659–2673. https://doi.org/10.5194/nhess-13-2659-2013

Mileti, D. S. (1995). Factors related to flood warning response. *US-Italy Research Workshop on the Hydrometeorology, Impacts, and Management of Extreme Floods*, 1–17.

Morss, R. E., Demuth, J. L., Lazo, J. K., Dickinson, K., Lazrus, H., & Morrow, B. H. (2016). Understanding public hurricane evacuation decisions and responses to forecast and warning messages. *Weather and Forecasting*, *31*(2), 395–417.

Mu, D., Kaplan, T. R., & Dankers, R. (2018). Decision making with risk-based weather warnings. *International Journal of Disaster Risk Reduction*, *30*, 59–73.

Ntelekos, A. A., Georgakakos, K. P., & Krajewski, W. F. (2006). On the uncertainties of flash flood guidance: Toward probabilistic forecasting of flash floods. *Journal of Hydrometeorology*, *7*(5), 896–915.

NWS. (2019). *Impact-based Flash Flood Warnings Factsheet*. https://www.weather.gov/media/wrn/FFW-IBW-factsheet.pdf

NWSUS. (2021). *Flash Flooding Definition*. https://www.weather.gov/phi/FlashFloodingDefinition

OCCC, C. O. of C. C. (2020). *L'impacte de la tempesta Gloria. Informe intern. O cina Catalana del Canvi Climàtic.*

Oktari, R. S., Munadi, K., & Ridha, M. (2014). Effectiveness of dissemination and communication element of tsunami early warning system in Aceh. *Procedia Economics and Finance*, *18*, 136–142.

Pagano, T. C., Hartmann, H. C., & Sorooshian, S. (2002). Factors affecting seasonal forecast use in Arizona water management: a case study of the 1997-98 El Niño. *Climate Research*, *21*(3), 259–269.

Pappenberger, F., Cloke, H. L., Parker, D. J., Wetterhall, F., Richardson, D. S., & Thielen, J. (2015). The monetary benefit of early flood warnings in Europe. *Environmental Science & Policy*, *51*, 278–291.

Pascual R., Cuevas G., Roa A., R. J. and R. B. (2020). *Storm Gloria 2020. The European Forecaster.*

Perera, D., Seidou, O., Agnihotri, J., Mehmood, H., & Rasmy, M. (2020). Challenges and Technical Advances in Flood Early Warning Systems (FEWSs). In *Flood Impact Mitigation and Resilience Enhancement*. IntechOpen.

Potter, S. H., Kreft, P. V., Milojev, P., Noble, C., Montz, B., Dhellemmes, A., Woods, R. J., & Gauden-Ing, S. (2018). The influence of impact-based severe weather warnings on risk perceptions and intended protective actions. *International Journal of Disaster Risk Reduction*, *30*(March), 34–43. https://doi.org/10.1016/j.ijdrr.2018.03.031

Potter, S., Harrison, S., & Kreft, P. (2021). The Benefits and Challenges of Implementing Impact-Based Severe Weather Warning Systems: Perspectives of Weather, Flood, and Emergency Management Personnel. *Weather, Climate, and Society*, *13*(2), 303–314. https://doi.org/10.1175/wcas-d-20-0110.1

Radianti, J., Tronslien, M. N., Moland, M. E., Kulmus, C. A., & Thomassen, K. K. (2017). A crisis management serious game for responding extreme weather event. *International Conference on Information Systems for Crisis Response and Management in Mediterranean Countries*, 131–146.

Rigo, T., Pineda, N., & Bech, J. (2010). *Analysis of warm season thunderstorms using an object-oriented tracking method basedfile:///Users/Eduardo 1/Downloads/water-13-01730-v2.pdf on radar and total lightning data*. *September*. https://doi.org/10.5194/nhess-10-1881-2010

Ripberger, J. T., Silva, C. L., Jenkins-Smith, H. C., & James, M. (2015). The influence of consequence-based messages on public responses to tornado warnings. *Bulletin of the American Meteorological Society*, *96*(4), 577–590.

Ritter, J., Berenguer, M., Corral, C., Park, S., & Sempere-Torres, D. (2020). ReAFFIRM: real-time assessment of flash flood impacts–a regional high-resolution method. *Environment International*, *136*, 105375.

Rogers, D., & Tsirkunov, V. (2011). Costs and benefits of early warning systems. *Global Assessment Rep*.

Roscoe, J. T. (1975). *Fundamental research statistics for the behavioral sciences [by] John T. Roscoe*.

Rossi, C., Falcone, G., Frisiello, A., & Dominici, F. (2018). *Best practices on Public Warning Systems for Climate-Induced Natural Hazards*. *September*.

Sai, F. (2016). *Mainstreaming impact based forecasting and warning in Bangladesh*. *September*.

Santanach, P. (2013). Primer estudi tectònic a Catalunya: l'estructura de la serralada Prelitoral per Domingo Palet y Barba. *Treballs Del Museu de Geologia de Barcelona*, *19*, 13–47. https://doi.org/10.32800/tmgb.2013.19.0013

Scolobig, A., Prior, T., Schröter, D., Jörin, J., & Patt, A. (2015). Towards people-centred approaches for effective disaster risk management: Balancing rhetoric with reality. *International Journal of Disaster Risk Reduction*, *12*, 202–212. https://doi.org/10.1016/j.ijdrr.2015.01.006

Shah, M. A. R., Douven, W., Werner, M., & Leentvaar, J. (2012). Flood warning responses of farmer households: a case study in U ria U nion in the B rahmaputra flood plain, B angladesh. *Journal of Flood Risk Management*, *5*(3), 258–269.

Sukhwani, V., Gyamfi, B. A., Zhang, R., AlHinai, A. M., & Shaw, R. (2019). Understanding the barriers restraining effective operation of flood early warning systems. *International Journal of Disaster Risk Management*, *1*(2), 1–19.

Sutton, J., Vos, S. C., Wood, M. M., & Turner, M. (2018). Designing effective tsunami messages: Examining the role of short messages and fear in warning response. *Weather, Climate, and Society*, *10*(1), 75–87.

Tapsell, S. M., Burton, R., Parker, D. J., & Oakes, S. (2004). The social performance of flood warning communications technologies. *Environment Agency, Technical Report W5C-016, ISBN*, *1*(84432), 434.

Terti, G., Ruin, I., Kalas, M., Lorini, V., & Sabbatini, T. (2017). From Forecasters to the General Public: A Communication Tool to Understand Decision-making Challenges in Weather-related Early Warning Systems. *AGU Fall Meeting Abstracts*, *2017*, NH43B-03.

Thornthwaite, C. W. (1948). An approach toward a rational classification of climate. *Geographical Review*, *38*(1), 55–94.

Twigg, J. (2003). The human factor in early warnings: risk perception and appropriate communications. In *Early warning systems for natural disaster reduction* (pp. 19–26). Springer.

UNDRR. (2019). *Global Assessment Report on Disaster Risk Reduction (GAR).* https://gar.undrr.org/report-2019

UNISDR. (2006). *EWC III THIRD INTERNATIONAL CONFERENCE ON: Developing Early Warning Systems: A Checklist*. Technischer Bericht, UN Inter-Agency Secretariat of the International ….

UNISDR. (2015). Sendai Framework for Disaster Risk Reduction 2015 – 2030. *Third UN World Conference in Sendai, Japan, 18th March 2015.* http://www.unisdr.org/files/43291_sendaiframeworkfordrren.pdf

Urgell i Vidal, M. (2008). *Els conflictes de la conca del riu Tordera*.

Weyrich, P., Ruin, I., Terti, G., & Scolobig, A. (2021). Using serious games to evaluate the potential of social media information in early warning disaster management. *International Journal of Disaster Risk Reduction*, *56*(February), 102053. https://doi.org/10.1016/j.ijdrr.2021.102053

Weyrich, P., Scolobig, A., Bresch, D. N., & Patt, A. (2018). Effects of impact-based warnings and behavioral recommendations for extreme weather events. *Weather, Climate, and Society*, *10*(4), 781–796. https://doi.org/10.1175/WCAS-D-18-0038.1

WMO. (2015). *WMO Guidelines on Multi-hazard Impact-based Forecast and Warning Services* (Issue 1150). https://library.wmo.int/doc_num.php?explnum_id=7901

Woolson, R. F. (2007). Wilcoxon signed-rank test. *Wiley Encyclopedia of Clinical Trials*, 1–3.

Young, Adele; Meléndez-Landaverde, Erika; Mastrantonas, Nikolaos; Gómez-Dueñas, Santiago; Speight, L. (2021). *An interdisciplinary approach to Forecasting and Early Warning Systems*. https://meetingorganizer.copernicus.org/EGU21/session/38934

Younis, J., Anquetin, S., & Thielen, J. (2008). The benefit of high-resolution operational weather forecasts for flash flood warning. *Hydrology and Earth System Sciences*, *12*(4), 1039–1051.

Zschau, J., & Küppers, A. N. (2013). *Early warning systems for natural disaster reduction*. Springer Science & Business Media.

Appendices

Appendix A – Evaluation survey

Section 1. Introduction

Thanks for taking this short (10 minutes) and voluntary survey!

Centre de Recerca Aplicada en Hidrometeorologia
UNIVERSITAT POLITÈCNICA DE CATALUNYA

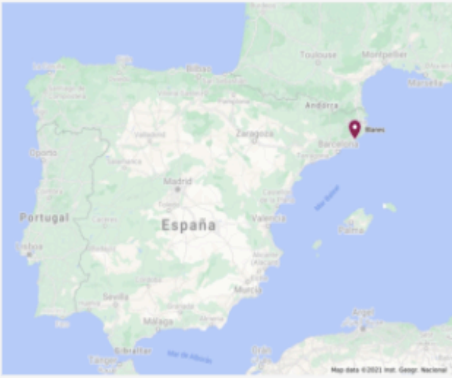
Erasmus Mundus FLOODRisk Master
Global Change • Hydroinformatics • Planning

By completing this survey, you are helping the **Centre of Applied Research on Hydrometeorology of the Polytechnic University of Catalonia** (CRAHI-UPC) to understand how flood early warnings systems can be **improved**.

Your answers will be used exclusively for **research purposes** and will remain **anonymous**. By taking this survey, you are giving your consent for your responses to be used in this research. If you have any questions or comments about the research, please contact **Eduardo Lucena** at lucena@crahi.upc.edu.

Section 2. Instructions

In this survey, you will be presented with 2 different scenarios in which you will have to **play the role** of the **manager of a kindergarten**. The kindergarten is located in a **flood-zone area** next to the Tordera River, in Blanes, Spain.



The kindergarten offers education to **children** from 4 months to 3 years old. All the classrooms and recreation areas are located on the **ground floor**. This means that a flood event could potentially cause **injuries or loss of life** due to the local vulnerabilities of the site.

In each scenario in this experiment, you will receive a warning message from a **different** local flood early warning system. In each case, you will have the evaluate the warning message and make **decisions** as the manager of the kindergarten. The forecast information is usually accurate, but false alarms can happen.

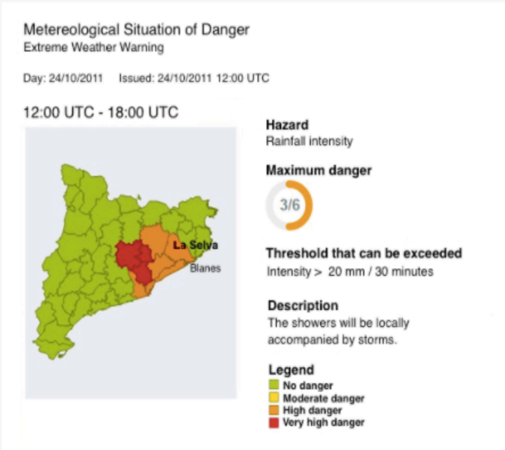
The self-protection plan for emergencies of the kindergarten indicates that the children should be **evacuated** to a neighbouring school in case a **severe flood** happens. However, be aware that an evacuation would cause **unnecessary costs and distress** if a flood event did not occur.

Section 3 (or 4). Hazard-based Early Warning System evaluation

Scenario:

Suppose you live in the town of Blanes, Spain. You are the **manager of a kindergarten** (preschool) in Blanes. It is **2 p.m.**, on a **Monday**.

You see the following **weather warning** issued by the local meteorological service for the next day (**Monday**) for your area. The warning emitted by the local meteorological service indicates a high level of danger for **rainfall intensity** in the county of La Selva, where the town of Blanes is located.



*1. Regarding this **warning message**, how strongly do you **agree** or **disagree** with each of the following statements? Please select one option per row.

	Strongly disagree 1	Slightly disagree 2	Neither agree nor disagree 3	Slightly agree 4	Strongly agree 5
1. The warning is **easy** to understand	○	○	○	○	○
2. I find it easy to understand the **possible impacts** of the weather event at the kindergarten	○	○	○	○	○
3. The warning makes me **concerned** for my safety and for the safety of children at the kindergarten	○	○	○	○	○
4. Based on the warning, I understand the **threats to my safety and the safety of other people** at the kindergarten	○	○	○	○	○
5. I believe the message to be **credible**	○	○	○	○	○
6. Based on the warning it is clear to me how I should **modify my behaviour** at the kindergarten, if necessary	○	○	○	○	○
7. The warning message gives me **enough information** to take **mitigation measures** at my workplace	○	○	○	○	○
8. I believe the message to be **useful** to my **decision-making process** in case of an emergency at the kindergaten	○	○	○	○	○

*2. After receiving this warning message, how **likely** is it that you would take the following **actions**? Please select one option per row.

	Extremely unlikely 1	Somewhat unlikely 2	Medium likelihood 3	Somewhat likely 4	Virtually certain 5
1. I would **remain alert** regarding the weather conditions, but would keep up with the school activities during the afternoon (2p.m. to 6p.m.)	○	○	○	○	○
2. I would check out **for other sources of information** via my smartphone for confirmation or advice	○	○	○	○	○
3. I would **interrupt** the school activities immediately (2p.m.) and proceed with an **evacuation** from the children to a safer place	○	○	○	○	○

*3. How **confident** are you in making your **decisions** above? Please select one option per row.

	Not confident at all 1	Slightly confident 2	Somewhat confident 3	Fairly confident 4	Completely confident 5
	○	○	○	○	○

*4. In this event, would you like to have received any other information? Please explain your answer.

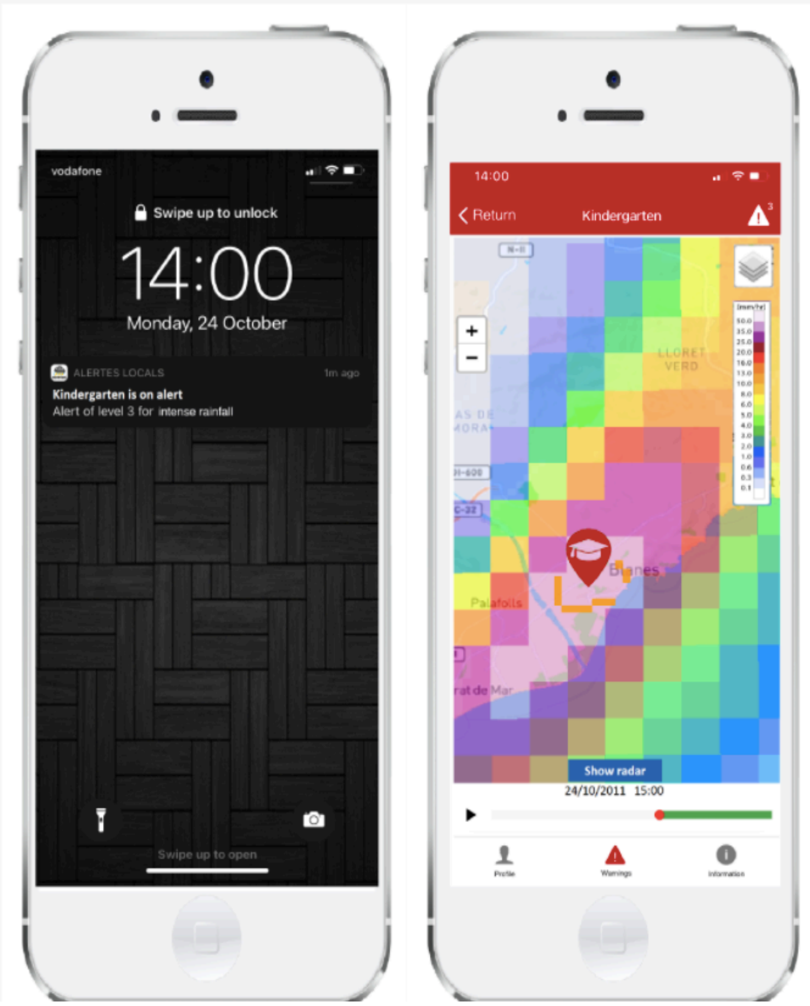
Section 4 (or 3). Site-specific Early Warning System evaluation (Part a)

Scenario:

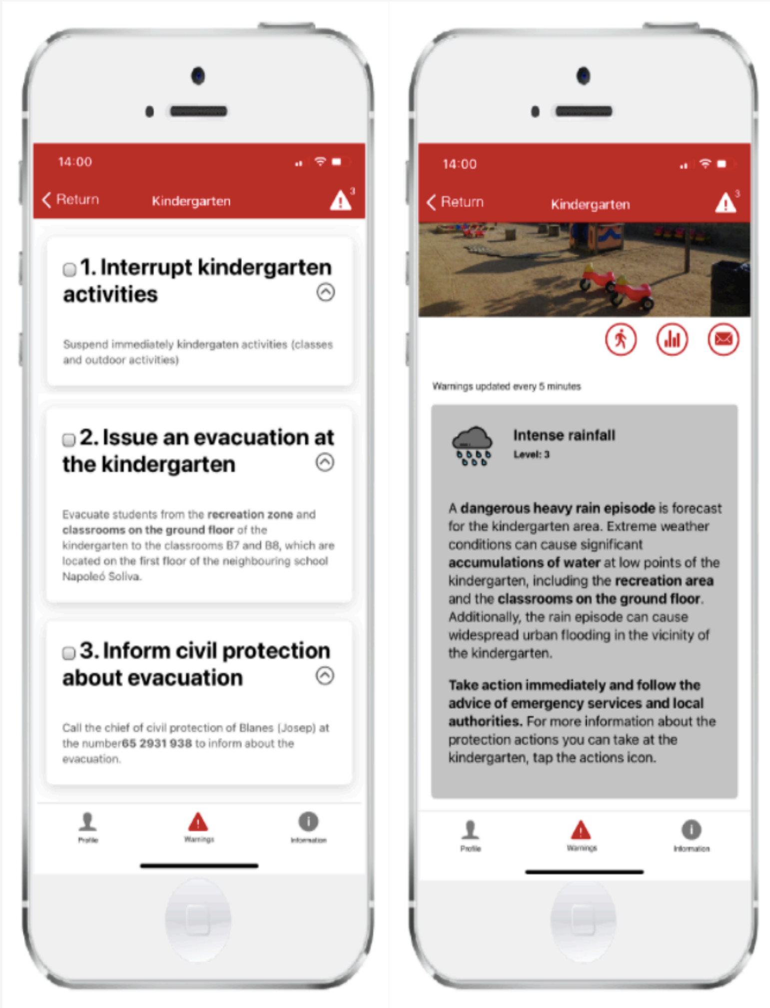
Suppose you live in the town of Blanes, Spain. You are the **manager of a kindergarten** (preschool) in Blanes. It is **2 p.m.**, on a **Monday.**

You receive the following warning message via a push notification on your smartphone. The warning is emitted by a local official flood warning system.

1. Push notification (homescreen), 2. Map



3. Warning message, 4. Recommended self-protection actions



*1. Regarding this **warning message**, how strongly do you **agree** or **disagree** with each of the following statements? Please select one option per row.

	Strongly disagree 1	Slightly disagree 2	Neither agree nor disagree 3	Slightly agree 4	Strongly agree 5
1. The warning is **easy** to understand	○	○	○	○	○
2. I find it easy to understand the **possible impacts** of the weather event at the kindergarten	○	○	○	○	○
3. The warning makes me **concerned** for my safety and for the safety of children at the kindergarten	○	○	○	○	○
4. Based on the warning, I understand the **threats to my safety and the safety of other people** at the kindergarten	○	○	○	○	○
5. I believe the message to be **credible**	○	○	○	○	○
6. Based on the warning it is clear to me how I should **modify my behaviour** at the kindergarten, if necessary	○	○	○	○	○
7. The warning message gives me **enough information** to take **mitigation measures** at my workplace	○	○	○	○	○
8. I believe the message to be **useful** to my **decision-making process** in case of an emergency at the kindergaten	○	○	○	○	○

*2. After receiving this warning message, how **likely** is it that you would take the following **actions**? Please select one option per row.

	Extremely unlikely 1	Somewhat unlikely 2	Medium likelihood 3	Somewhat likely 4	Virtually certain 5
1. I would **remain alert** regarding the weather conditions, but would keep up with the school activities during the afternoon (2p.m. to 6p.m.)	○	○	○	○	○
2. I would check out **for other sources of information** via my smartphone for confirmation or advice	○	○	○	○	○
3. I would **interrupt** the school activities immediately (2p.m.) and proceed with an **evacuation** from the children to a safer place	○	○	○	○	○

*3. How **confident** are you in making your **decisions** above? Please select one option per row.

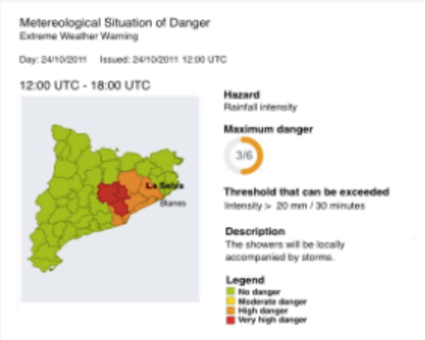
	Not confident at all 1	Slightly confident 2	Somewhat confident 3	Fairly confident 4	Completely confident 5
	○	○	○	○	○

*4. In this event, would you like to have received any other information? Please explain your answer.

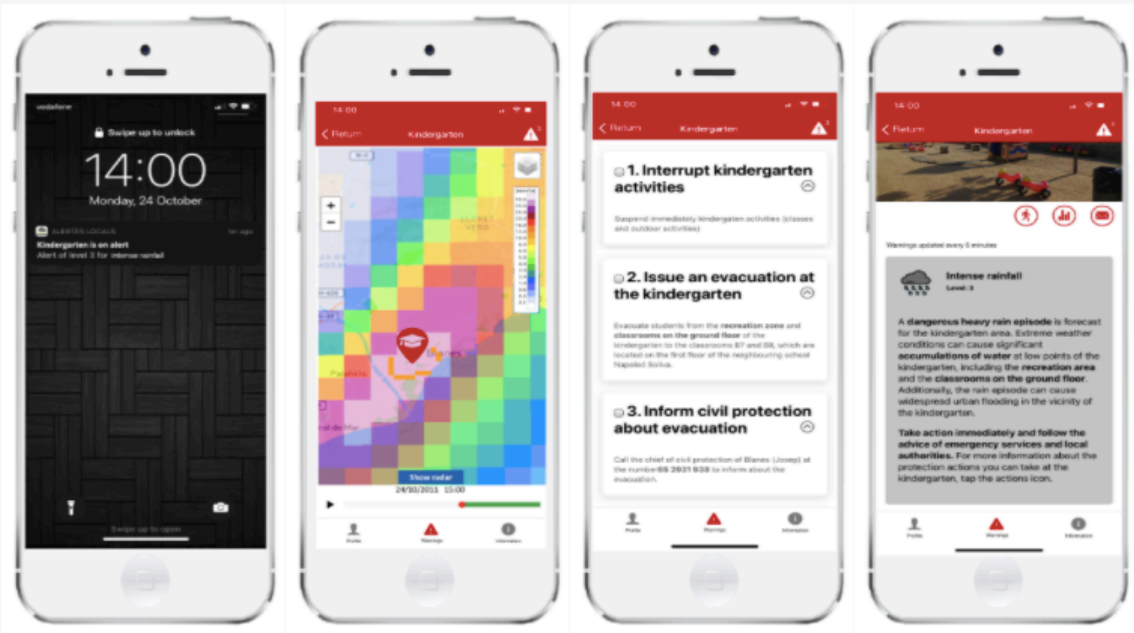
Section 5. Direct comparison between EWSs

Please now answer the following questions based on the comparison of the 2 early warning systems.

1. General hazard-based warning system:



2. Site-specific impact-based warning system:



Please select only **one** option per row.

	1. General hazard-based early warning system	2. Site-specific impact-based early warning system
1. Which system do you **prefer?**	○	○
2. Which system made you feel **more confident** while taking a decision?	○	○
3. Which system would you more likely **recommend** to a friend?	○	○
4. Which system had warning messages that were **easier** to understand?	○	○
5. Which system made you more **aware** of the **flood risk** in the kindergarten?	○	○

Section 6. Participant's general information

*1. What is your gender?

- Male
- Female
- Other
- Prefer not to say

*2. How old are you?

Please choose...

*3. What is your highest level of education?

- No school qualifications
- Secondary school qualification
- Trade certificate, professional certificate or diploma
- University undergraduate degree (e.g., Diploma or bachelor's degree)
- University postgraduate degree (e.g., Honours, Masters, Ph.D.)

*4. What is your current occupation?

*5. Have you ever experienced a flood event?

- No
- Yes

6. If you said yes to Q5, were you affected in some way by the flood?

- No
- Yes

Please enter your comment here:

Section 7. Final page

Thanks for taking part - your answers are valuable!

Centre de Recerca Aplicada en Hidrometeorologia
UNIVERSITAT POLITÈCNICA DE CATALUNYA

Erasmus Mundus FLOODRisk Master
Global Change • Hydroinformatics • Planning

If you have any questions or comments about the research, please email Eduardo Lucena at lucena@crahi.upc.edu.