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Design and evaluation of a community and impact-based site-specific early warning system (SS-EWS): The SS-EWS framework

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Abstract

The recent extreme rainfall events in Spain such as the storm Gloria have highlighted the gaps in emergency communication, particularly the disconnect between the available impact-based early warning systems (IBEWSs) and the steps communities take during emergencies. This paper presents a community-centred framework named 'site-specific early warning system' (SS-EWS) to co-design and co-evaluate with communities an IBEWS for vulnerable locations within high-risk areas. The components of the framework guide communities in identifying and evaluating local impacts; establishing impact and advisory tables; deriving impact-based rainfall thresholds and warning levels; and configuring the SS-EWS with radar-based nowcasting and numerical weather prediction (NWP) models. A first implementation and evaluation of the SS-EWS have been done for a public school, two ford crossings and the city of Terrassa, Spain. The SS-EWS shows promising results in triggering location-based or site-specific warnings compatible with the reported impacts and proposing actions to reduce the local risk. Furthermore, the combination of NWP and radar-based nowcasting improved the capacity of the SS-EWS to monitor the evolution of the precipitation and capture highly intense rainfall. The SS-EWS can be a straightforward and cost-efficient complement for regional EWS to increase the preparedness of communities.

KEYWORDS

emergency management, forecasting and warning, pluvial flooding, risk communication

1 | INTRODUCTION

Early warning systems (EWSs) are crucial for national and local disaster risk reduction (DRR) strategies and the achievement of the Sendai Framework for Disaster Risk Reduction (SFDRR) targets (UNISDR, 2015). In recent years, national meteorological and hydrological services (NMHSs) have made substantial advancements in their capacity and precision to forecast extreme rainfall events (Corral et al., 2019). However, lives continue to be lost, and extensive damage is still observed. Although timely warnings are issued in most situations, they do not guarantee that recipients will effectively understand the message and that actions will be performed to reduce the local impacts (Weyrich et al., 2018).

Events such as the deadly 2021 floods in Europe highlight the need for EWSs to connect forecasts with the vulnerabilities and response capacities of at-risk communities. As established by the SFDRR (UNISDR, 2015), effective DRR measures must enable 'risk-based' decision-making by understanding all aspects of hazard, exposure and vulnerabilities to increase community preparedness, resilience and adaptation. Consequently, designing an effective community-based EWS requires the identification of the target population, their needs, response capabilities and the best available protective action to decrease their risk during emergencies (Cova et al., 2017). To support this shift towards 'people-centred' EWSs, The World Meteorological Organization (WMO) has suggested the implementation of impact-based EWSs (IBEWSs) across NMHSs. That is, systems able to communicate 'what the weather will do', focusing on the expected damages and the clear guidelines on what citizens and authorities can do to reduce their risk. However, the lack of systematic vulnerability and impact databases, technological resources, verification procedures and established partnerships with all actors involved can transform IBEWSs into a complex objective, especially for small and vulnerable communities that are usually ungauged and with limited resources. In the recent survey by Kaltenberger et al. (2020) with 32 NMHSs, most participants believed they could not afford to implement and run impact models for IBEWS. Moreover, previous research has focused on the uptake of impact-based warnings (IBWs) by the public (Meléndez-Landaverde et al., 2020) and little on how to design both the IBEWSs and the impact-based thresholds at a local scale (Potter et al., 2021). If communities are expected to implement IBEWS, they need guidance on exploiting their local risk knowledge to realistically develop a straightforward system within their capabilities. This paper describes a people-centred framework named 'site-specific EWS' (SS-EWS) to co-design and co-evaluate with community representatives an IBEWS for specific vulnerable points within high-risk areas. The SS-EWS uses meteorological, local vulnerability and exposure information to derive impact-based rainfall thresholds for triggering site-specific warnings (SSWs). These warnings communicate impacts communities could experience during rainfall events at these 'high-risk' sites alongside protection actions to support actionable decisions. Thus, this work presents the SS-EWS framework and a first community-scale evaluation. The SS-EWS has been implemented in Terrassa, Spain and co-evaluated (from 2020 through 2021) by comparing the triggered warning levels, the actions performed and the observed impacts.

The paper is structured as follows: Section 2 describes the study area. Section 3 presents the SS-EWS. Section 4 deals with the results and discussion of the design and performance of the SS-EWS. Finally, some concluding remarks are presented in Section 5.

2 | CASE STUDY

2.1 | Terrassa, Spain

The city of Terrassa (70.1 km^2 and 223,627 inhabitants) is located in Catalonia, Spain, at altitudes from 160 to 937 masl (Figure 1a) (Statistical Institute of Catalonia, 2020). Two ephemeral rivers surround Terrassa: The Arenes and Palau, both part of the Llobregat basin, and the Vallparadís stream, a natural park with protected cultural heritage (Figure 1b). The prevailing climate is a warm-temperature Mediterranean, characterised by mild winters and high-temperature summers (Prohom & Salvà, 2011). The mean annual precipitation is 536 mm, mainly concentrated from September to May. High-intensity rainfall events are frequent during this period, some becoming torrential and causing significant urban floods and rivers to overflow. Notably, the extreme flood in September 1962, one of the most severe flash floods (FFs) recorded in Spain (Pino et al., 2016), is annually commemorated. It left widespread damage and over 800 casualties after 250 mm of rainfall fell in 3 h (Martín-Vide & Llasat, 2018).

In 2019, the municipality disseminated a survey to collect the awareness and understanding of citizens regarding the local risks.[1] The results indicate that 54% of the participants ($n = 439$) perceived weather-induced hazards and their impacts as the main risk to which Terrassa is vulnerable, with floods leading the list. Consequently, the municipality decided to implement an EWS based on the SS-EWS to support the actions and self-protection responses at high-risk locations. Moreover, since 2015 the region of Catalonia has required that all activities within risk areas develop and implement an official self-protection plan to be activated in case of emergencies (Departamento de Interior, 2015). In this context, the SS-EWS has been co-designed and co-evaluated for the city of Terrassa, a public school located in the flood-prone area of the Vallparadís stream and two ford crossings over the Palau river (Figure 1b). At the school, a hydraulic study identified that a section of the classrooms is exposed to severe and rapid water accumulations in case of intense rainfalls surpassing the drainage network capacity. According to their self-protection plan, students must evacuate to the higher-ground classrooms after receiving an official warning for rainfall intensity. However, the COVID-19 pandemic forced the authorities to change the evacuation to a nearby building due to the imposed sanitary measures limiting students per

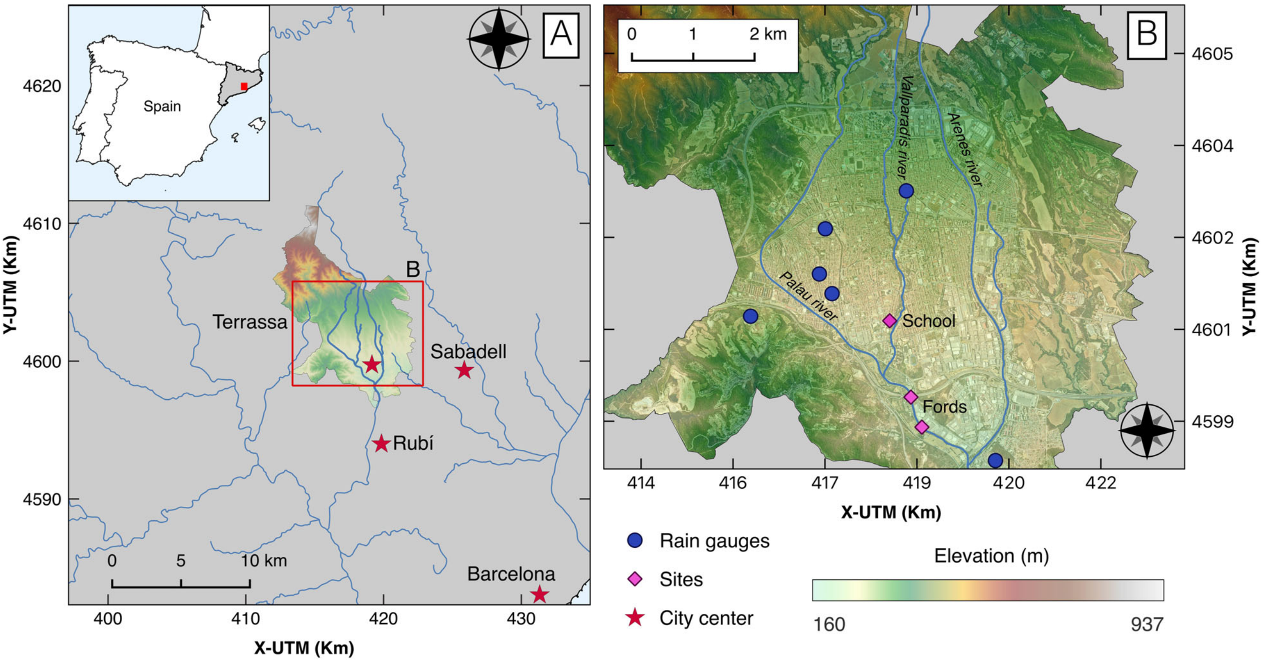

FIGURE 1 (a) The city of Terrassa. (b) Location of the hydrometeorological sensors and selected vulnerable sites.

TABLE 1 Source of historical rainfall data

Historical rainfall					
Data source	**Station**	**Period**	**No. of years**	**Resolution**	**Analysis performed**
Terrassa rain gauges	Plaça de la Creu	1999–2021	21 years	30 min	Return periods
					Impact evaluation
		1965–1998	33 years	Daily	Return periods
					Evaluation of historic events

classroom. Finally, the two fords are in the southern part of the Palau river, next to an industrial area. They are highly vulnerable to overtopping due to fast-flowing water. In 2018, a citizen lost his life in this location while driving across the river during an intense rainfall episode. The municipality installed automatic gates in 2020 to close the fords when a user-defined threshold is reached as a preventive action. The SS-EWS is foreseen to act as a trigger for the official emergency actions at the sites and the activation of the flood municipal emergency plan of Terrassa.

2.2 | Hydrometeorological data

A limited number of official rain gauges—as well as independent stations that are available to the municipality—monitor the area of Terrassa (Figure 1b). As shown in Table 1, rainfall data has been compiled from the rain gauge located in the city with the longest record to support the definition of impact-based rainfall thresholds. Unfortunately, the Palau river discharge data is unavailable since the gauge stations have recently been installed.

Terrassa is also covered by the C-Band Doppler radar network operated by the Meteorological Service of Catalonia (SMC). The spatio-temporal resolution of the operational radar QPE and QPF (providing up to 2 h lead-time nowcasting) is 1000 m and 6 min. A radar and rainfall-based FF-EWS developed by the Centre of Applied Research in Hydrometeorology of the Polytechnic University of Catalonia (CRAHI-UPC) is currently operational at the SMC and the Water Agency of Catalonia. It uses the basin-aggregated rainfall over the drainage network (explained in Section 3) to derive FF warnings at any point of the drainage system. During the H2020 ANYWHERE project,[2] the FF-EWS was improved and now runs at a 200 m resolution over the entire Catalonia region. Finally, the 1-h rainfall accumulation forecasts up to $H+48$ from the European Centre for Medium-Range Weather Forecast, integrated forecasting system is used to extend the lead-time

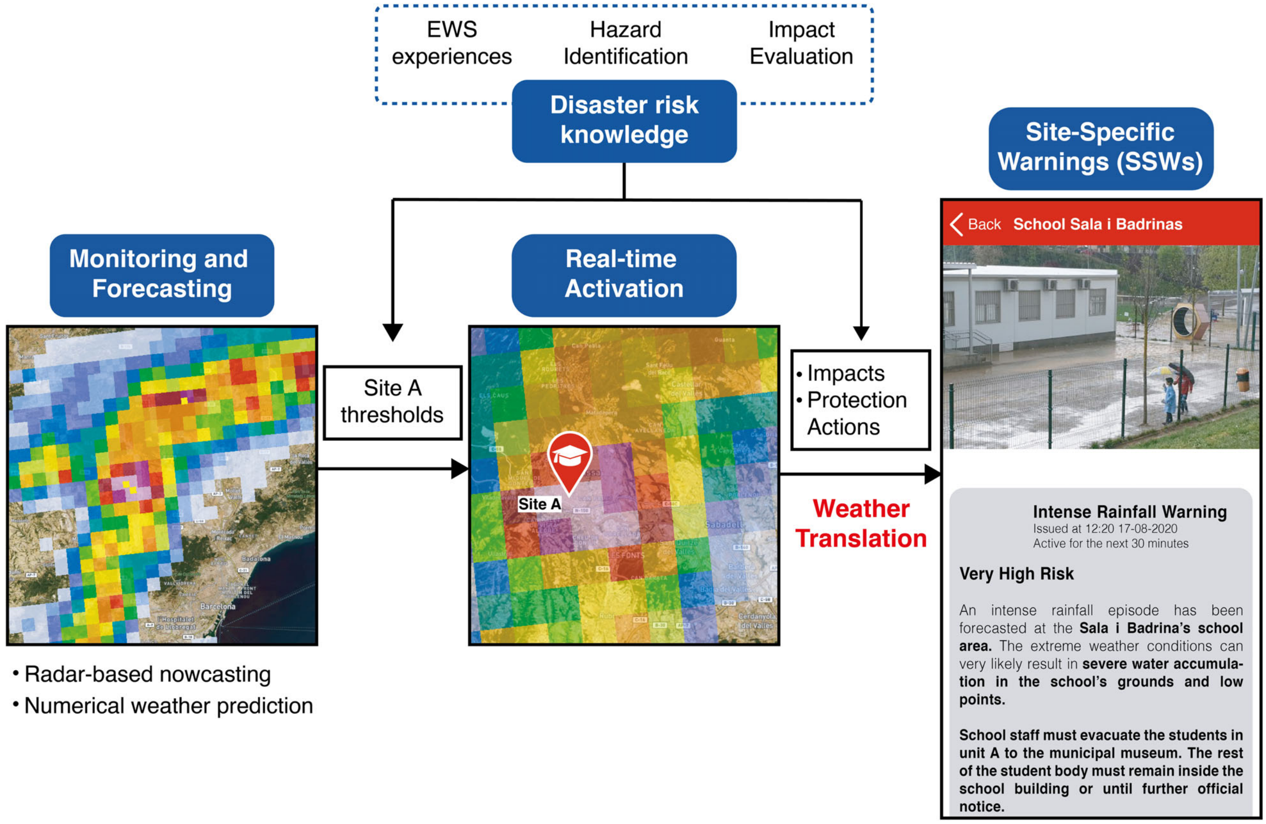

FIGURE 2 The site-specific early warning system (SS-EWS) framework. The blue boxes represent the four components of the framework.

and capture events characterised by significant rainfall accumulations in longer periods of time.

3 | COMMUNITY AND IMPACT-BASED EWS: THE SS-EWS FRAMEWORK

The SS-EWS is divided into four components (Figure 2). To carry out the co-design, implementation and co-evaluation of these elements, the framework adopts a community-based work scheme consisting of quantitative and qualitative data collection methods (work meetings, focus groups, mixed-method questionnaires and interviews) with selected local stakeholders, hereafter community representatives. In this context, the information from the mixed-method questionnaire and interviews creates a baseline for subsequent improvements, helps guide the discussions of the focus groups and facilitates the collection of local knowledge data. Furthermore, the work meetings help to understand and expose the current warning needs and gaps, and present the SS-EWS work plan and the progress made regarding the co-design stages. Finally, the focus groups aim to discuss and make collective decisions regarding the local SS-EWS components and the direction of the system for the community and sites.

For the co-design and evaluation of the SS-EWS in Terrassa, the community representatives consisted of an interdisciplinary group ($n = 18$) from the responsible authorities, first responders and local experts in disaster risk management.

3.1 | Disaster risk knowledge

This component aims to understand the local risk communication strategies and analyse the characteristics that can make the community and specific locations highly exposed and vulnerable during rainfall events. The expected outcomes are rainfall-based thresholds coupled with (i) the expected impacts on the community or specific sites (impact-based thresholds), (ii) the official emergency or self-protection plans and (iii) the adapted SSW messages.

3.1.1 | Current strategies in flood communication: EWS experiences and obstacles

DRR strategies have been negatively affected when local perception was overlooked, as policymakers, scientists and communities perceive risks differently (Bradford et al., 2012). Thus, identifying how communities understand and view local EWS is essential for developing a trusted SS-EWS that triggers appropriate self-protection actions from individuals to further increase their resilience (Twigger-Ross et al., 2014). Factors such as trust, community context, experiences with EWS and failure to understand hazard information can shape the decision-making process of individuals when presented with warnings (O'Sullivan et al., 2012). Therefore, to design a community-based SS-EWS, it is fundamental to evaluate the local EWS from the perspective of communities to collect their impressions regarding the current system, its advantages, disadvantages and areas for improvement. Furthermore, this evaluation can create a baseline for proposing and evaluating solutions according to the needs and requirements of the community. Consequently, and similar to previous studies (Bradford et al., 2012; Lalancette & Charles, 2022), self-completion mixed-method questionnaires (see Table 2) and interviews on emergency communication aspects, experiences and impressions were performed with the community representatives.

3.1.2 | Hazard and impact identification

There is a long history of using non-scientific reports to recreate natural disasters and their impacts (Barriendos et al., 2014). In their review, Tschoegl et al. (2006) found that newspaper reports are a significant information source in many international and national hazard databases. However, as Guzzetti and Tonelli (2004) identified, newsworthiness bias can lead to less accurate descriptions of what news outlets perceived as minimal impacts, especially for local events. Nevertheless, the contribution of these sources to flood-related impact data collection remains important (Escobar & Demeritt, 2014). In line with previous research, the SS-EWS uses the information provided by regional news outlets, social media, official reports from the authorities, insurance data and the recollection of the community representatives to detect local events and create a hazard-impact database. For each identified event, the local impacts are divided into four categories: (i) Danger to citizens (e.g., evacuations, rescue, injury or death); (ii) Damage to buildings; (iii) Disruption of transport; and (iv) Others, that encompasses emergency information (e.g., 112 calls) and complementary data (e.g., insurance claims and impact descriptions).

Likewise, historical rainfall data and official flood maps are revised, and a rainfall frequency analysis is performed to derive return periods. This hazard information is cross-referenced to the previously identified events to contextualise their categorised impacts in frequency, observed flood extent, and rainfall accumulations.

TABLE 2 Summary of the mix-method survey sections, the associated questions and statements

Survey sections	Response options
Perceptions regarding the current EWS in Terrassa	
What do you consider are the principal advantages?	Free-form answers
What do you consider are the principal disadvantages?	
What would you change?	
Statements	
The current rainfall warnings:	1 = strongly disagree
- Facilitate fast local decisions	2 = disagree
- Are useful for the emergency management process in Terrassa	3 = neither agree nor disagree
- Are easy for people to understand	4 = agree
- Are reliable	5 = strongly agree
- Allow for a proper understanding of possible local impacts	
- Have an appropriate amount of local impact information	
- Have an appropriate amount of local impact information for the general public to make self-protection decisions	
- Have an appropriate amount of local impact information for your community sector to make self-protection decisions	
- I am satisfied with how the current rainfall warnings support my decision-making process	
- I am satisfied with the amount of time I have to take emergency actions after receiving a warning	
Local impacts	
For your community sector/specific site:	Free-form answers
What do you consider are low/medium/high impacts triggered by rainfall events?	
What actions have you taken to mitigate those impacts?	
Can you mention the approximate dates when these impacts occurred?	

Abbreviation: EWS, early warning system.

3.1.3 | Impact evaluation

All identified events of the hazard-impact database are co-evaluated and categorised with the community representatives on an impact severity three-level scale (low, medium and high). Although it involves a degree of subjective expert judgement, a participatory approach involving local representatives can support the assessment of the acceptable levels of risk for the community and provide critical vulnerability detail to broader risk information (Maskrey et al., 2019). Through the focus group scheme, impact and advisory tables are co-developed for the community and specific-sites. These individual tables present the events and their impacts categorised by severity and provide appropriate self-protection or emergency actions to reduce the identified impacts. Finally, the outcomes of this evaluation with the hazard identification stage (hazard-impact database) enable establishing initial critical warning thresholds per severity level, based on impacts, coupled with the frequency (e.g., return periods) and observed rainfall accumulations. This approach follows the future trend indicated by Kaltenberger et al. (2020), where many European NMHSs expect to use subjective impact-based criteria to produce and trigger weather warnings in the next 5 years. However, due to past and future modifications in vulnerability and exposure levels caused by mitigation actions or changes in requirements of end-users, these impact-based rainfall thresholds must be frequently reviewed. As suggested by IFRC (2020), these can be adjusted on an event-by-event basis or after every rainy period.

3.2 | Monitoring and forecasting

The SS-EWS follows a rainfall-based approach by using radar-based nowcasting and numerical weather prediction (NWP) to issue local warnings. It compares the precipitation accumulated for a duration (D) in a pixel (or group of pixels) to a corresponding reference associated with a statistical frequency of occurrence (e.g. return period in years) or an impact-based threshold. Previous studies on using a rainfall-based approach to trigger warnings from radar-based nowcasting have found that the results can be as reliable as those based on rainfall-runoff models for return periods over 10 years (Corral et al., 2019; Versini et al., 2014). Table 3 presents the SS-EWS issues warnings based on: (i) the local rainfall accumulations and (ii) the basin-aggregated rainfall. Although these warnings do not consider urban drainage, they have proven to be fast and suitable for alerting pluvial and river floods (FFs) driven by intense precipitation (Alfieri et al., 2019).

3.2.1 | Warnings based on the local rainfall

These warnings are calculated from the precipitation accumulated for a defined duration at all the neighbouring pixels that drain to a specific-site. When durations equal to 30 min are selected, warnings are especially useful for alerting floods in urban environments or sensitive areas due to intense precipitation (Alfieri et al., 2019). Likewise, durations equal to 12 and 24 h can enable the system to monitor and detect upcoming rainfall events characterised by large accumulations with the help of NWP forecasts. For the warning level computation at a specific-site, a comparison is made between the forecasted rainfall accumulation for defined durations at all the draining pixels and the local impact-based thresholds. The maximum exceeded threshold of all the neighbouring pixels defines the warning level for the site.

3.2.2 | Warnings based on the basin-aggregated rainfall

This type of warning is calculated assuming that the FF hazard of a point, in terms of the exceeded return period, can be characterised by the rainfall accumulated upstream (i.e., the basin-aggregated rainfall;

TABLE 3 Characteristics of the two types of warnings in the SS-EWS

Type of warning	System	Product	Spatial resolution	Temporal resolution	Units
Local rainfall	Numerical weather prediction	24-h rainfall accumulation	9000 m	12 h	Millimetres (mm)
		12-h rainfall accumulation	9000 m	12 h	
	Radar-based nowcasting	30 min rainfall accumulation	1000 m	6 min	
Basin aggregated rainfall	Radar-based nowcasting	FF hazard in return period years	200 m	6 min	$T = [0, 2, 5, 10, 25, 50, 100, 200, 500]$

Abbreviations: FF, flash flood; SS-EWS, site-specific early warning system.

Corral et al., 2019). For a given pixel in the drainage network, the basin-aggregated rainfall is accumulated for a duration equal to the concentration-time of the basin defined by this pixel. This forecasted accumulated rainfall is then compared to the reference values of the basin-aggregated rainfall for different return periods (using Intensity-Duration-Frequency curves built from regional climatology) to determine the value of the exceeded return period for the upcoming event. The outcomes of the FF-EWS in Catalonia are used in the framework to assess the FF hazard in the drainage network. Therefore, the warning level of a community or specific site at risk within a flood-prone area is determined by comparing the exceeded return period from the FF-EWS in a given time with the established thresholds from the impact evaluation.

3.3 | Real-time activation

The impact-based rainfall thresholds serve as triggers for the warnings presented in the previous section. In the SS-EWS, the final warning level of a specific site is determined by the maximum level between the two warnings. However, to improve the adaptability of the system to the community needs, a set of operators (e.g., AND) can be applied to the individual thresholds of both warnings. These operators are helpful when more than one exceeded threshold is required by stakeholders for issuing a warning of a certain level. As a default, once a warning level is triggered, it remains active for 30 min unless a higher status is reached. However, specific research should be done to define the appropriate timeframe for each community.

3.4 | Site-specific warnings

The SSWs are location-specific messages; thus, their impact information and behavioural recommendations are based on the outcomes of the impact and advisory tables. Additionally, images from the previously identified events are included to increase the understanding and personalisation of the warning to the local context (Morss, Mulder, et al., 2016).

Finally, a crisis app has been designed together with the SS-EWS. The app can disseminate the SSWs, the official active alerts in the region and the weather information from radar-based nowcasting and NWP. However, the detailed description of the design, functionalities and end-user evaluations are beyond the scope of this paper.

4 | RESULTS AND DISCUSSION

The results obtained applying the SS-EWS framework are presented here. The first sections focus on the co-design process with the community representatives in Terrassa to define the components of the SS-EWS for the city and specific-sites. Finally, the performance of the system is presented for the period 2020–2021.

4.1 | Emergency communication in Terrassa: Obstacles and barriers

As a first step in the community-based work scheme, the self-completion mixed-method questionnaire (see Table 2) was disseminated to the community representatives ($n = 18$). The results from the first section indicate that the main disadvantage of the warnings in Terrassa is their perceived disconnection from the community context. The official warnings issued by the SMC have a regional risk dimension that might not accurately represent what the communities, especially the most vulnerable ones, are experiencing. However, this is not an isolated situation. The study carried out by Kaltenberger et al. (2020) shows that currently, only a few NMHs in the EU issue warnings on a municipality level. Previously identified challenges such as the amount of local information and resources required are some reasons behind this lack of municipality implementations.

Nonetheless, there is a clear recognition that a generic warning will not address the requirements of communities at risk in terms of vulnerability characteristics, level of exposure, and communication needs (Fernández-Bilbao & Twigger-Ross, 2009). An inadequate assessment of these factors can lead to inappropriate reactions or lack of responses during emergencies from communities (Mileti, 1995); as a representative recognised, *'The warnings in Terrassa are not locally accurate. As they are regionally orientated, it frequently happens that we receive a warning, but it does not represent the situation in Terrassa. So, for the next time a warning is issued, people take them less into account'*. Receiving an official warning is not enough to guarantee a response suitable to the local context from individuals at risk (Casteel, 2016). An effective people-centred EWS must empower communities to reduce the consequences that extreme rainfall events could have in their daily lives (WMO, 2018).

When asked what improvements they would make to the current EWS in Terrassa, representatives expressed through the questionnaire and post-discussions that the system includes the local context in the forecasts and warnings. By receiving localised impact-based warning communication, representatives explained they could better understand the upcoming events, when to activate their emergency plans and the appropriate actions. The official warnings in Terrassa focus on the evolution of parameters (e.g., intensities) and do not provide information regarding potential impacts or behavioural recommendations. The step forward that SS-EWS represents in the IBW concept proposes a technique based on the assumption that it can help trigger protective responses and improve warning comprehension (WMO, 2015). In experimental studies made by Meléndez-Landaverde et al. (2020), Weyrich et al. (2018), Morss, Demuth, et al. (2016) and Morss, Mulder, et al. (2016), the inclusion of impact information into warnings increased the likelihood of making protective decisions during emergencies of at-risk individuals. However, Potter et al. (2018) reported that although IBWs were easier to understand, they did not influence the decision-making process of end-users. Prior contradictory results from these studies confirm the complexity of designing warnings to effectively support communities during emergencies. Nevertheless, focused flood risk content generated by the SS-EWS can help increase the likelihood that individuals will undertake appropriate and effective protection actions (Yamada et al., 2011).

Finally, the reasons why risk communication might fail are diverse. Distrust and low confidence in warning accuracy and reliability can lead to passive responses (Parker et al., 2009). Clearly, emergency communication will have little positive impact without trust and credibility from recipients (O'Sullivan et al., 2012). For Terrassa, representatives expressed that the current disseminated warnings were unreliable ($n = 18$, 72%). Although a complex process, previous studies indicate that one step to fostering and improving trust is by constructive, open interactions with community representatives from the start of any DRR strategy (Bradford et al., 2012). By openly engaging with community representatives in all stages of the SS-EWS, this exercise could help create a positive, trustworthy relationship between all members; expose any misconceptions regarding the system; improve the usefulness and credibility of the outcomes; and build a shared vision for managing local flood risk (Maskrey et al., 2019). In this context, future research should focus on the influence of the SS-EWS framework on aspects such as levels of trust, cooperation, and credibility among communities.

4.2 | Impact identification and evaluation: Critical thresholds and self-protection actions

From mid-2020 to late 2021, five work meetings and three focus groups were held to define the impact tables, the first group of impact-based rainfall thresholds and their linked protection actions.

Ahead of these sessions, a hazard-impact database for Terrassa was developed. Between 1999 and 2019, 15 hydrometeorological events negatively affected Terrassa. Urban and river flooding due to intense rainfall were identified as the main triggers of local impacts. Events characterised by large accumulations in extended periods were not considered problematic for Terrassa. The impacts from these events were classified according to the criteria presented in Section 3 and cross-referenced with the recorded rainfall accumulations, exceeded return periods and flood maps when applicable. For events before 2010 (seven), the insurance database for flood-related claims from the Spanish Insurance Compensation Consortium served as an additional verification point while also providing a view of the damages in the area.

Based on this compilation and classification, impact tables for Terrassa, schools and fords focused on the safety of citizens were developed. Through the focus group sessions, the representatives classified events from the database based on their previous experiences and local knowledge of the impacts. For the city scale, the need for rescue activities due to fast-flowing water or high-water accumulations in well-known problematic flood-prone sections of streets (e.g., low points) were classified as a high-impact. In this regard, the rescue of citizens trapped in their cars is reported frequently during intense rainfall episodes at Terrassa. However, this is not an uncommon event. Ruin et al. (2007) found that drivers are likely to underestimate flood risk, leading to dismissed warnings. Finally, for the school and the two fords, the flooding of the classrooms in the lowest part of the terrain and the danger to the lives of citizens caused by overtopping from fast flowing water of the Palau river were identified as the main high-impacts. Local appropriate local self-protection actions from pre-approved emergency plans for the specific sites and Terrassa were coupled with the classified impacts to generate the advisory tables (see Table 4).

Finally, the hazard database and the impact tables served as a foundation to derive a set of impact-based rainfall thresholds for the three warning levels (see Table 5). Thus, the SS-EWS operates on the assumption that the impacts seen on the previously identified events

TABLE 4 Impact and advisory tables

Site	Level 1: Pre-alert		Level 2: Alert		Level 3: Emergency	
	Impacts	Actions	Impacts	Actions	Impacts	Actions
Terrassa	Small and isolated flooding of lands and flood-prone areas	Active monitoring of the situation and the latest forecast	Localised flooding of lands and roads causing possible danger to life due to fast-flowing water and overtopping. Disruption of travel time is expected	Revision of the municipal emergency plan and preparation of resources (personnel and equipment)	Widespread flooding of lands and roads causing danger to life due to fast-flowing water and overtopping. Evacuations and rescue actions may be required	Activation of the municipal emergency plan
School	Little or no disruption of school activities	Active monitoring of the situation and the latest forecast	Possible water accumulations at the school grounds, affecting the east modules	Cancellation of all outdoor activities. Revision of the self-protection plan and preparation of the emergency equipment	Flooding of the school grounds, affecting the east modules	Activation of the school's self-protection plan. Evacuation of the school to the designated location
Fords	Little or no disruption of traffic at the fords	Active monitoring of the situation and the latest forecast	Possible danger to life due to fast flowing water overtopping the fords	Monitoring of water levels and preparation of resources (personnel and equipment)	Danger to life due to fast flowing water overtopping the fords	Automatic closure of the ford's gates

TABLE 5 SSWs impact-based thresholds

Site	Level 1: Pre-alert	Level 2: Alert	Level 3: Emergency
Terrassa and fords	24 h/mm ≥ 40 mm	24 h/mm ≥ 60 mm	24 h/mm ≥ 100 mm
	12 h/mm ≥ 20 mm	12 h/mm ≥ 40 mm	12 h/mm ≥ 60 mm
	30 min/mm ≥ 15 mm	30 min/mm ≥ 20 mm	30 min/mm ≥ 30 mm
		FF hazard ≥ 2 T	FF hazard ≥ 5T
School	24 h/mm ≥ 40 mm	24 h/mm ≥ 60 mm	24 h/mm ≥ 100 mm
	12 h/mm ≥ 20 mm	12 h/mm ≥ 40 mm	12 h/mm ≥ 60 mm
	30 min/mm ≥ 15 mm	30 min/mm ≥ 25 mm	30 min/mm ≥ 35 mm

Abbreviation: SSW, site-specific warning.

can be expected when a warning level is activated in Terrassa due to the derived rainfall thresholds.

4.3 | SS-EWS configuration

Table 5 presents the set-up of the SS-EWS using local and basin-aggregated warnings triggered by impact-based rainfall thresholds. The logical operator OR activates the final SSW level in all locations. Thus, only one impact-based threshold must be exceeded to trigger a warning level. This decision was made to (i) capture simultaneous events (pluvial and fluvial) and (ii) improve the robustness of the SS-EWS. The system operates with two types of forecasts, radar-based nowcasting and NWP. In the first case, several recognised errors can affect the results of QPEs and the implementation of algorithms (e.g., blending of radar QPE maps with rain-gauge measurements) to mitigate their effect are needed (Park et al., 2019). Although this correction is applied in real-time for the Catalonia region (Corral et al., 2009), it still depends on the availability of gauge observations. Nevertheless, the lack of calibration parameters and the high resolution of the local radar-based QPE maps allow identifying the areas at risk with high resolution at the expense of a shorter lead time (up to 2 h; Alfieri et al., 2019). In this context, the SS-EWS can enable earlier preparedness and effective activation of response plans by extending this time horizon with impact-based thresholds activated through NWP models, as suggested by Versini et al. (2014). The current SS-EWS configuration enables monitoring of the evolution of potentially dangerous situations while enhancing the ability to detect the location and timing of convective rainfall, responsible for a large part of the emergencies in Terrassa.

4.4 | Performance of the SS-EWS for the 2020–2021 period

Different rainfall episodes between 2020 and early 2021 caused mild to severe impacts in Terrassa. From these, three events are presented to illustrate the performance of the SS-EWS. They differ in rainfall types, seasonal occurrence and impacts observed.

As suggested by the WMO (2021), the evaluation stage of IBEWS, and SS-EWs, requires a different approach than the typical EWSs. Limited access to considerable and systematic impact data can hinder the direct assessment of impact and warning levels through common indicators (Ritter et al., 2020). Therefore, the review of the SS-EWS is not limited to only the occurrence of the event. As proposed in previous studies of IBWS, the SS-EWS co-evaluation focuses on the analysis between the triggered warning levels, the performed associated self-protection actions (Potter et al., 2021) and the reported impact severity based on the established criteria for Terrassa. Table 6 presents the maximum values of the individual warnings alongside the reported impacts in Terrassa and the sites for the three events.

4.4.1 | Event 1: 20th–23rd January 2020

Between 19th and 23rd January 2020, Spain was affected by the extratropical cyclone Gloria, characterised by historic high winds, heavy rainfall (Figure 3), landslides (Palau, 2021) and coastal floods (Amores et al., 2020). Gloria caused a record-breaking event of widespread flooding across Catalonia, leaving extensive damage, casualties, and more than 500 evacuations and rescue activities of people trapped in their cars (Consejo de Ministros, 2020). From the 20th at 00:00 UTC to the 23rd at midnight, Terrassa accumulated 120 mm, with the 21st as the most critical day. Even though rainfall intensities were light (a maximum of 9 mm/30 min), the daily accumulation reached 75 mm, lower than the 5-year return period (88 mm). As shown in Table 6, Terrassa experienced localised floods on roads and lowland areas, with high winds causing the most impacts.[3] Although river floods due to overtopping were not reported, the fords, flood zones and public parks were closed off as a preventive measure. The school did not report any incidence beyond the cancellation of outdoor activities.

At 00:00 UTC on 21st January, the SS-EWS issued an SSW level 2 (alert) based on local rainfall for the next 24 h. This SSW corresponded to an NWP forecast for a daily accumulation over 65 mm, similar to the recorded accumulation. As a result of the observed light intensities, no additional SSWs were issued. The activated SSW level 2 (alert) is considered consistent with the reported impacts caused by rainfall in all sites and the actual protection decisions made for the school and Terrassa city. As identified in Section 3, significant accumulations in extended periods are not the primary source of impacts in Terrassa. Even though the fords were closed off as a preventive measure due to the forecasted rainfall accumulation of the storm Gloria across Catalonia, Terrassa did not experience impacts caused by river floods. The SS-EWS issued an SSW level 2 (alert) at the fords with the close monitoring of the situation as a preventive action, a combination considered compatible with the reported impacts.

Furthermore, this event highlights the advantage of using NWP in combination with radar-based nowcasting to extend the time horizon of the SS-EWS. Its use improved the capacity to monitor the evolution of the rainfall accumulation caused by the storm Gloria, despite the current low spatial accuracy, and to trigger warnings appropriate to the local context of Terrassa. Accordingly, the issued SSWs can help communities prepare for future emergencies or self-protection actions needed throughout the day. Finally, the SS-EWS can only issue SSWs, coming from a rainfall-based approach to help reduce the impacts caused by river and pluvial floods. However, Gloria and its impacts due to high winds showcase the need to include more types of hazards in the configuration of the SS-EWS. Although the framework could be adapted, this study evaluates the system and its components with the initial proposed design.

TABLE 6 Maximum warning values and the reported impacts at Terrassa, the school, and the ford crossings for the three studied events

		NWP forecast		Radar forecast			
Event	**Site**	**24 h (mm)**	**12 h (mm)**	**30 min (mm)**	**FF hazard (T)**	**Maximum warning level**	**Real impacts reported**
21st January 2020	Terrassa	65	30	6	–	2	+200 calls to the 112 line and +300 actions performed. Localized floods on roads and low points. High-risk, flood areas and public parks closed. Public transport disrupted. Localized power outages.
	School			4	N/A	2	No severe impacts reported. All outdoor and extra activities cancelled.
	Fords			5	–	2	Manually closed off as a preventive measure. Videos of the fords covered by debris (but not overtopped).
16th August 2020	Terrassa	3	2	36	2Y	3	+90 calls to the 112 line. Videos showing an increase of the Palau and Arena's River discharge. Manholes displaced. A woman had to be rescued from her car due to high surface water accumulations. Official warning for intense rainfall was issued after the event had ended.
	School			36	N/A	3	No impacts
	Fords			34	2Y	3	The fords were overtopped by flowing water (videos around 17:30 UTC). Automatic gates remained opened.
29th April 2021	Terrassa	4	2	25	–	2	No significant damage. Pictures of citizens jumping across flowing surface water.
	School			19	N/A	1	Students remained in their classrooms, with no relevant impacts reported.
	Fords			24	–	2	The gates were automatically closed. No overtopping on the fords.

Abbreviations: FF, flash flood; NWP, numerical weather prediction.

4.4.2 | Event 2: 16th August 2020

On 16th August, Terrassa experienced an intense convective rainfall event typical of the summer periods. Although short (from 16:00 to 18:00 UTC), the maximum recorded accumulation reached up to 40 mm, causing water accumulations and displacement of manhole covers in roads,[4] flooding of underground parking, fallen trees and rescue actions (Table 6). These observed impacts across Terrassa fall within the high-impact criteria established with the representatives. Locations around water bodies and the fords became dangerous during the event, with videos showing the Palau river overtopping them.[5] Nevertheless, the automatic gate system of the fords remained open, causing citizens to question the reasoning behind this action on social media. In the school, incidents were not reported due to the buildings being vacant for the summer break. Had this not been the case, the school would have started a late evacuation since the SMC warning for rainfall intensity, the trigger for their self-protection plan, was activated after the rainfall had ceased (18:00 UTC).

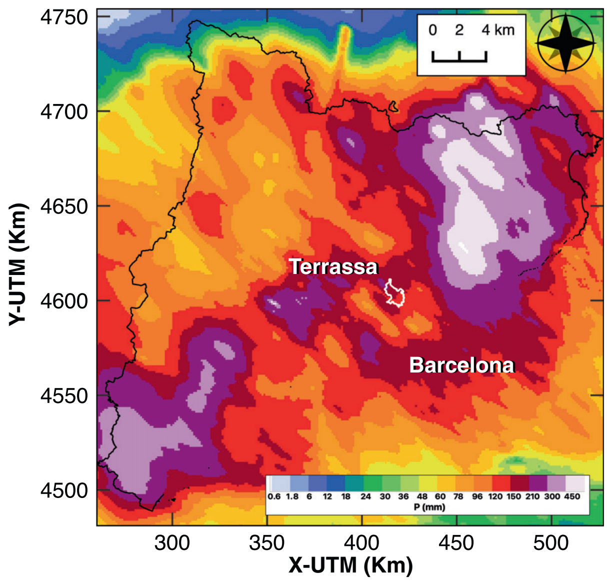

FIGURE 3 Accumulated rainfall from 20th January 2020 00:00 UTC to 23rd January 2020 23:00 UTC. The white line represents the outline of Terrassa.

Figure 4 shows the maximum warning levels based on radar-based rainfall accumulation and basin-aggregated rainfall forecasts issued by the SS-EWS at 16:30 UTC (1 h before the most significant impacts were observed). The NWP local rainfall accumulations of 24 h and 12 did not exceed the thresholds, thus producing no SSWs (see Table 6). However, the radar-based rainfall forecast triggered an SSW level 3 (emergency) for Terrassa city, the school and the fords. The first panel of Figure 4 (Figure 4a) shows the 30-min accumulation forecasted for 17:30 UTC (1 h lead-time), anticipating the most intense convective pixels of the day (over 35 mm accumulated in 30 min, a value higher than the 20-year return period). Simultaneously, the FF-EWS pixels of the Palau river network associated with the fords surpassed the 2-year return period, resulting in an SSW level 2 (alert) due to the warning coming from the basin-aggregated rainfall (Figure 4b). However, because of the SS-EWS configuration (OR operator), the final SSW level for the fords reached level 3: emergency (similar to the school and Terrassa) due to the high intensity of the local rainfall (Figure 4c). In this context, had the gates been operational with the SS-EWS as a trigger, they would have been automatically closed according to their linked emergency action. Likewise, the school self-protection plan and the emergency plan of Terrassa would have

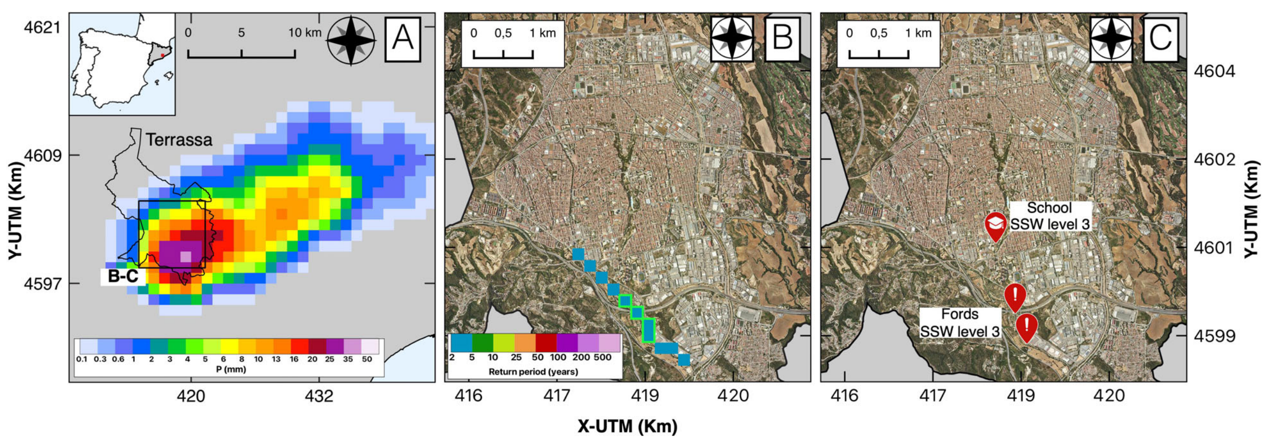

FIGURE 4 Results obtained for the 16th August 2020 event at 16:30 UTC for 17:30 UTC, based on (a) 30-min rainfall accumulation and (b) basin-aggregated rainfall. The river network pixels associated with the ford crossings are identified with a green line. (c) SSW levels triggered at 16:30 UTC. SSW, site-specific warning.

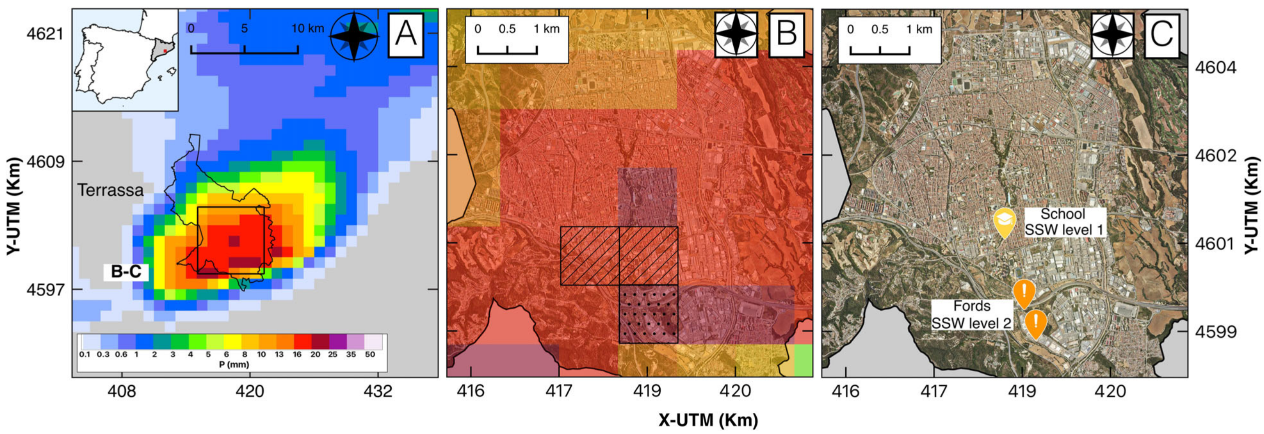

FIGURE 5 Results obtained for the 29th April 2021 event at 12:48 UTC for 13:18 UTC, based on (a) 30-min rainfall accumulation. (b) The neighbouring pixels drain to the school (lines) and ford crossings (dots). (c) Site-specific warning levels triggered.

been activated. These triggered SSW levels and actions are consistent with the observed impacts between 16:30 and 17:30 UTC in Terrassa and the sites for the emergency level classification (Table 6). Additionally, this event showcases how the radar-based nowcasting in the SS-EWS allows triggering local SSWs driven by intense precipitation that the NWP tends to underestimate or miss (Alfieri et al., 2019).

4.4.3 | Event 3: 29th April 2021

A light short-term rainfall event was observed on 29th April in Terrassa. The event started at 11:18 UTC and lasted for 3 h. Due to the spatial distribution of the rainfall, sensors across Terrassa recorded different accumulations, with a maximum of 25 mm/30 min, slightly lower than the 5-year return period (26 mm). As shown in Table 6, no significant incidents were reported beyond localised water accumulation on roads. Images of citizens jumping across flowing surface water while walking were shared on social media,[6] showing the difficulties of getting around the city during the event. For the fords, the gates were automatically closed as the upper threshold of the river gauge was exceeded. Finally, at the school, the students remained in their classrooms with no significant incidents.

Figure 5 shows the maximum warning levels issued by the SS-EWS based on the local rainfall at 12:48 UTC. Although the warning level issued for Terrassa (level 2: alert) was considered too high by some representatives, those working in the emergency response sector view it as appropriate, highlighting the different requirements of decision-makers during emergencies and the need to identify and recognise them (Maskrey et al., 2019). However, all agreed that even though the situation had to be closely monitored, the automatic gates should have remained open as the Palau river never came to overtop the fords. As explained before, the water level used as a benchmark to automatically close the gates was not calibrated at that time.

The SS-EWS issued an SSW level 2 (alert) for the fords and proposed actions according to what the representatives had expressed (see Table 4). Furthermore, the SSW level differences (pre-alert vs. alert) between Terrassa, the school and the fords exemplify the benefit of using radar-based nowcasting to achieve a local SS-EWS. Its high resolution allows a good representation of the variability of the rainfall field (Versini et al., 2014). Thus, it can capture local intensities across the community and sites that rain gauges could potentially miss. Over the school pixels (Figure 5a,b), a maximum SSW level 1 (pre-alert) was triggered based on local rainfall, considered consistent with the reported impacts, and performed actions. The highest intensity at the school area was around 19 mm/30 min, equal to the 2-year return period and lower than the 24 mm/30 min over the fords. In this regard, the SS-EWS versus issued different SSW levels across the community and sites (Figure 5c). This is considered a satisfactory result, as one of the goals of the SS-EWS is to understand the different vulnerabilities to trigger impact-based rainfall warnings (SSWs) appropriate to the local context.

5 | CONCLUSIONS

IBEWSs have been promoted to address the gaps within the EWS communication chain under the assumption they can increase the understanding of individuals and generate more appropriate responses to reduce their risk. However, past events extreme events in Spain and Europe have exposed the gap between the available forecasting tools and the performed (or lack of) emergency actions by communities. This paper proposes the SS-EWS framework to guide and support the co-design and implementation of a simplified community-based IBEWS.

A first implementation of the SS-EWS was performed with community representatives for Terrassa and selected vulnerable points. The evaluation of the SS-EWS for 2020–2021 shows promising results in triggering SSW levels, using point and basin-aggregated rainfall forecasts, compatible with the reported impacts and proposing appropriate protection actions to reduce the local risk dynamically. By implementing site-specific thresholds within a community, rather than the regional thresholds used officially by the SMC, IBEWS can enable end-users to make local actionable decisions at sites with different vulnerability profiles. Moreover, the combination of NWP and radar nowcasting improved the capacity of the SS-EWS to monitor the evolution of the precipitation and capture highly intense rainfall events. The community-based approach at the centre of the SS-EWS allows it to be flexible and adaptable to the needs and requirements of communities with different levels of exposure and vulnerability profiles in Spain and similar regions. The Terrassa authorities currently use the SSW levels to trigger the corresponding protection actions in real-time through the city-scale operational version of the MH-EWS platform developed within the framework of the ANYWHERE-H2020. The SME HYDS is currently providing this operational platform to support the key exploitable results of the ANYWHERE-H2020 project under the commercial name ARGOS.

However, the SS-EWS has limitations. Similar to IBEWS, the lack of systematic impact data to verify and validate the SS-EWS can hinder it from being truly objective. Although it can be complemented with information collected from the community representatives, the impact-based threshold definition depends on the availability of historical rainfall, flood, and impact data. Moreover, there are uncertainties associated with the derivation of the impact-based thresholds and the quality of the rainfall inputs that can affect the results of the QPEs. Thus, the SS-EWS is not proposed as a replacement for regional EWS but as a straightforward, cost-efficient complement to increase the preparedness of vulnerable communities. Future research should focus on expanding the evaluation of the SS-EWS real-time performance across other regions, the uptake of the SSWs by the citizens and the evaluation of the dissemination channels (i.e., mobile applications). Finally, the SS-EWS can play a central role in promoting a shift towards resilient societies that understand their vulnerabilities and are prepared to respond and effectively reduce the impacts of extreme rainfall events.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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ENDNOTES

[1] Source: https://tinyurl.com/bddvt4zc

[2] Source: https://tinyurl.com/mr2b4kmf

[3] Source: https://terrassadigital.cat/nou-episodi-de-pluges-aquesta-matinada/

[4] Source: https://twitter.com/LaboriaMarc/status/1295048124629753858

[5] Source: https://twitter.com/alexeniainet/status/1295054686412832769

[6] Source: https://twitter.com/mmaserasf/status/1387766964567826433

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