Journal of Hydrology 602 (2021) 126708

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Review papers

Creating effective flood warnings: A framework from a critical review

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ARTICLE INFO

This manuscript was handled by Nandita Basu, Editor-in-Chief, with the assistance of Joseph H.A Guillaume, Associate Editor

Keywords:
Flood Early Warning System (FEWS)
Warning
Natural hazard
Risk communication
Disaster
Emergency management

ABSTRACT

As climate change is intensifying the frequency and severity of floods around the globe, adaptation is increasingly vital. Besides structural measures to mitigate flood risk, non-structural measures are known to be highly effective and low-cost. Such non-structural measures include Flood Early Warning Systems (FEWS). Effective warning creation and dissemination are crucial to successful FEWS. Despite extensive bodies of research that cross the boundaries between disciplines and application domains, systematic understanding of the detailed aspects contributing to the effectiveness of flood warnings is lacking. We systematically review the state-of-the-art in risk perception and warning communication present in academic (and grey) literature for FEWS. We focus on the elements of risk warnings specifically, rather than reviewing the topic of risk communication in general. We start with exploring how personal attributes affect individual risk perception related to flood warnings. We then deconstruct flood warnings into three basic components: content, format and dissemination channel. Most importantly, we found 21 individual elements (options) for these components, each associated with varying levels of support for their effectiveness in literature. Important caveats were identified, such as a lack of research into the speech format and SMS channel. We then describe and visualise the warning creation process, providing a framework for guidance. Accelerating technological advancement necessitates continued research into the effectiveness of novel formats and channels, rendering the currently most widely supported and researched elements increasingly obsolete. Further research is needed to explore the complex interplay between elements, i.e., how do different combinations impact effectiveness? Finally, little is known about the transferability of our findings to Africa, Asia and South America, as industrialised countries dominate the research. We hope our findings will contribute to improved understanding, and support the practice of creating effective flood warnings.

1. Introduction

1.1. Background

Floods are the most frequent and widespread natural disasters worldwide (WMO, 2013). With climate change, the frequency and severity of floods are projected to increase (Allen et al., 2019). Over the past decades, flood management has shifted from structural measures (i.e., physical flood protection structures) to non-structural measures, such as the distribution of flood warnings (UNISDR, 2018). Indeed, Early Warning Systems (EWS) can save lives and prevent damage, while having relatively low operational costs (Baudoin et al., 2014; Zhu et al., 2010). EWS are designed to predict incoming hazards and warn affected populations ahead of time. Flood Early Warning Systems (FEWS) have been installed in countries across the world (Acosta-Coll et al., 2018; CRED, 2015). Timely and accurate flood warnings can reduce the physical and psychological impacts of flooding (Munro et al., 2017). The need for early warning systems has been underlined by the United Nations through the Paris Agreement and the Sustainable Development goals (UN, 2015; UNFCCC (United Nations Framework Convention on , Climate Change), 2015), and has been further articulated in the Sendai Framework for Disaster Risk Reduction (UNISDR (United Nations International Strategy for Disaster Reduction), 2015).

Technological advances have made FEWS more accurate over the past two decades. However, the effectiveness of FEWS is just as dependent on the quality of the warning dissemination. Effective flood warnings inform the public about an impending flood and motivate them to take protective action (Morss et al., 2016; WMO, 2015). Literature distinguishes between two types of warnings: flood alerts and emergency warnings (Parker et al., 2009; Silver, 2015; Sutton and Kuligowski, 2019). Alerts are characterised by a higher lead-time (i.e., the time between warning issuing and predicted impact) and/or lower predicted impact compared to emergency warnings. The latter are used for more severe flood forecasts and shorter lead-times (Golding, 2009).

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https://doi.org/10.1016/j.jhydrol.2021.126708
Received 18 March 2021; Received in revised form 16 June 2021; Accepted 14 July 2021
Available online 21 July 2021

Flood warnings often fail to be received, understood or evoke adequate responses (O'Sullivan et al., 2012; Rollason et al., 2018; Sukhwani et al., 2019; Zhu et al., 2010). To reach all targeted audiences, both traditional media (e.g., radio and TV) as well as digital communication channels (e.g., web sites and applications, social media) should be employed for flood warning dissemination (Feldman et al., 2016; Lam et al., 2017; Liu et al., 2017). The inadequacy of responses to flood warnings has two common causes: low individual risk perception and a lack of self-efficacy (Hagemeier-Klose and Wagner, 2009; Morss et al., 2016; Shreve et al., 2016). Put simply, people underestimate the risk posed by floods and/or perceive themselves as unequipped to mitigate this risk. Thus, effective flood warnings should raise individual flood risk perception, hereby increasing the likelihood of recipients to follow recommended protective actions (Keller et al., 2006; Potter et al., 2018). To evoke adequate action among recipients, flood warnings should contain all the information required to take sufficient action (Khalid and Shafiai, 2015; Lindell et al., 2017; Rollason et al., 2018). Besides the characteristics of a warning itself, an individual's response to a flood warning is shaped by personal attributes (e.g., age, knowledge of hazard, trust in authorities) and situational factors (e.g., personal experience with floods, location of housing) that influence personal risk perception (Kellens et al., 2013; Lechowska, 2018; Wachinger et al., 2013).

To the best of our knowledge, only a few studies specifically evaluate flood warnings and their efficacy. Höppner et al. (2012) analysed 60 risk communication practices related to natural hazards, and their outcomes across Europe. Hagemeier-Klose (2007) reviewed tools used for issuing flood warnings across Europe at various spatial levels. A review of the impact of flood risk communication across multiple countries found low levels of information penetration and preparedness, correlated with high levels of distrust towards responsible authorities (O'Sullivan et al., 2012). However, abovementioned reviews focus on broader risk communication approaches (e.g., long-term trust building, educational campaigns), rather than exclusively on warning communication.

1.2. The components of flood warnings

Two types of flood warnings can be identified depending on their level of urgency. On the one hand, alerts are characterised by a higher lead-time (i.e., longer time between warning issuing and predicted impact), higher forecast uncertainty and/or lower predicted impact. On the other hand, emergency warnings are used for more severe flood forecasts and shorter lead-times (Golding, 2009). The remainder of this paper will simply refer to "warnings", including both types. Flood warnings are comprised of *content* (what, where, when, why), issued in a *format* (text, graphics, maps, face to face), which is distributed via a communication *channel* (radio, TV, Web page, SMS, etc.). We will call these three categories the *components* of flood warnings. We will refer to the individual options available for each component as the *elements*, which combine to form a complete warning. Although different variations are reported in literature, the categorisation we adopt aligns well with the academic consensus on the core components of hazard warnings (Bean et al., 2015; Höppner et al., 2012; Mayhorn and McLaughlin, 2014; Mileti and Peek, 2000). The earliest categorisation of components was developed by Covello et al. (1986), who identified four components in risk communication messages: the source, message design, channel and target audience. More recently, Salman and Li (2018) suggested three components: message, messenger and media.

This review explores the broad spectrum of individual flood warning elements that have been tested and discussed in literature. We found novel elements that show significant potential for flood warning applications, warranting significantly more research attention. We refer to the process of combining different elements into a coherent warning dissemination as the warning development process.

1.3. Aim and objectives

To our knowledge, there have been few scholarly attempts to create an overview of the elements of effective flood warning communication. Furthermore, recent studies point to a mismatch in practice between the warnings issued, and the types of information that warning recipients seek and are able to comprehend (Johnson et al., 2018; Mays et al., 2019; Sukhwani et al., 2019). This paper aims to uncover how to increase the effectiveness of flood early warnings. Therefore, we critically and systematically review the academic literature on flood warning communication, complemented with some grey literature, to establish and organise the elements of flood warnings and their reported performance in practice. We thus provide a framework to guide the effective production and dissemination of flood warnings. Three objectives support our aim: (i) explore how personal attributes affect individual risk perception related to flood warnings, (ii) establish the-state-of-the-art on the elements of flood warning communication and (iii) provide a framework to guide flood warning creation.

We start our review with organising the most prominent factors influencing individual flood risk perceptions. We proceed by exploring warning elements found in literature and build a conceptual framework that synthesises the available research on of the building blocks of flood warnings. Our framework furthermore provides an overview of the empirical evidence on the efficacy of each warning element, as reported in literature. We identify knowledge gaps and promising future avenues of research. We finish by giving a schematic representation of the warning development process. We foresee two important contributions from this review: (i) academic; identification and conceptualisation of the important building blocks for the creation of flood warnings, based on evidence literature and (ii) practical; aiding flood warning creation by providing practitioners (e.g., emergency management authorities) with a practical framework for warning creation in a broad set of contexts.

2. Research approach

2.1. Literature selection

We employed the systematic review method *Preferred Reporting Items for Systematic Reviews and Meta-Analysis* (PRISMA) developed by Moher et al. (2009). This method comprises four main steps: (i) formulating keywords and questions, (ii) selecting databases and search methods, (iii) classifying and selecting criteria to group documents and (iv) extracting and synthesising the findings. Using the electronic databases Scopus and Web of Science, we conducted our literature search between November 2019 and March 2020 (Fig. 1). We extended our search to include warning communication for natural hazards beyond only floods, if deemed generalizable. For example, Sutton et al. (2014) test the effectiveness of warnings tweets sent during a canyon wildfire. To ensure the inclusion of relevant articles that our search failed to identify, we then applied a snowball sampling method (Jalali, 2013), using highly relevant papers (e.g., Höppner et al., 2012; Kellens et al., 2013; Lechowska, 2018; Wachinger et al., 2013). While the initial literature search focused solely on academic publications, this selection also included highly relevant grey literature. After removing duplicates, we manually screened the articles by reading the abstract and excluded those we judged not to be related to our search terms. While no hard exclusion criteria were used, soft criteria of exclusions included when abstract keywords referred to unrelated topics, such as: risk management for natural hazards, disaster management, risk mitigation via protective actions, willingness-to-pay research, and technical reports/guides demonstrating new/current natural hazard warning systems. To increase the relevance and quality of our findings, we limited the search to papers published in peer-reviewed journals between the years 2000 and 2020, however, during the peer-review process three extra papers were added, two of which were from 2021. We did so, assuming that the

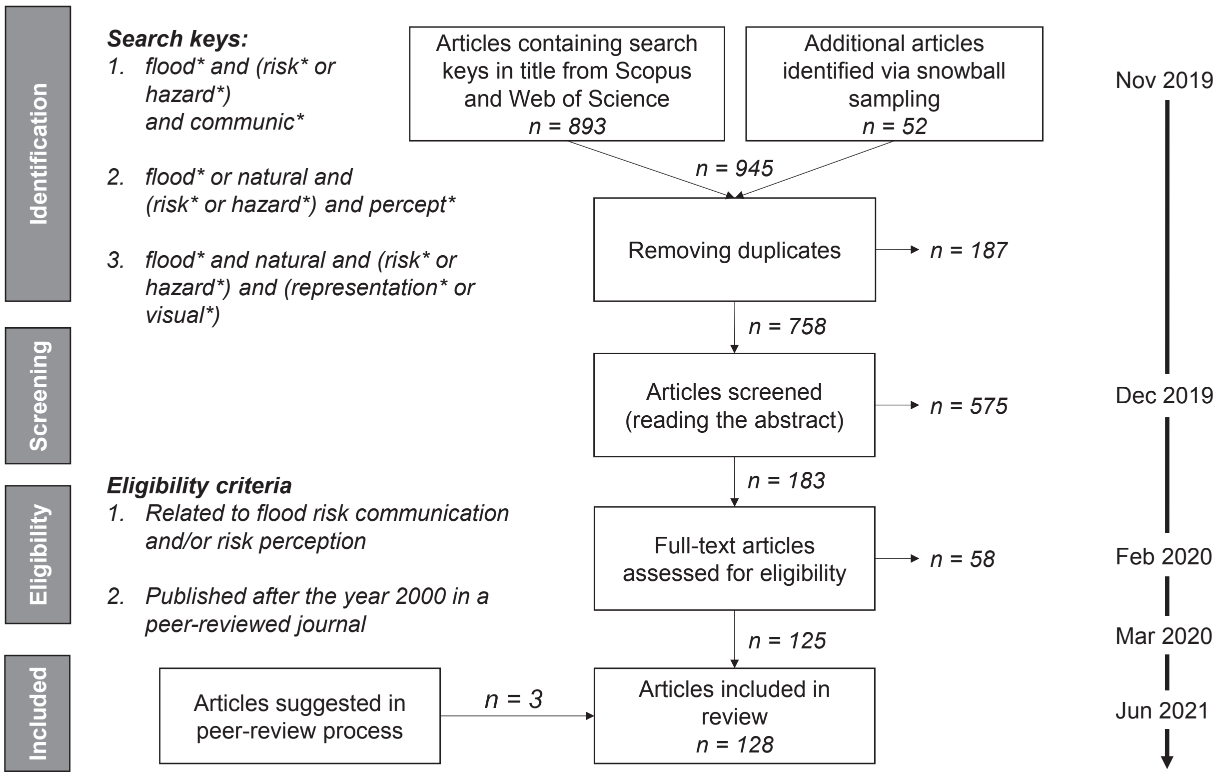

Fig. 1. Literature review method flow diagram, following PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis; Moher et al. (2009)).

resulting papers build on the work preceding the year 2000, but are more relevant to current-day communication technology, which has changed significantly over the past decades (Alexander, 2014; Stephenson et al., 2018). We added two highly relevant papers from before 2000, as they were identified as very important by the reviewed literature (Covello et al., 1986; Lipkus and Hollands, 1999). The final number of articles included in the review is 128 (Fig. 1).

We performed a meta-analysis of the resulting collection of articles in a spreadsheet, collecting statistics on year of publication, geographic focus of the research and type of research or methodology. For the latter aspect, eight types of research were distinguished. Two types of reviews: literature review and content review. The latter indicates a review of documents other than academic literature, such as warning messages. Six types of research papers were distinguished based on their main data gathering method: case studies, content analyses, (i.e., of actual warnings), experiments, interviews, surveys and workshops. We added a ninth category for studies that included more than one of the above eight methodologies: mixed-methods.

The effectiveness of flood warnings depends on their ability to alter recipients' risk perception. Therefore, personal attributes affecting an individual's risk perception need to be considered when developing and issuing warnings. Thus, we distilled a list of the most important personal attributes influencing flood risk perception from literature. Unlike previous studies, we specifically focused on risk perception factors related to flood warning communication. Our selection process followed three steps. Firstly, we analysed the selected articles by collecting all attributes mentioned. Secondly, we filtered the acquired list by retaining only those instances where a significant effect of the attribute on risk perception was reported by the authors. Thirdly, we selected those attributes that were identified in at least three separate studies.

2.2. Analysis of the attributes affecting risk perception

A number of factors unrelated to warning and alert messages themselves affect the way risk communication is perceived by recipients. Such factors, or attributes, are important to consider when designing risk communication. During our literature search, we gathered attributes from relevant literature reviews that analysed natural hazard and risk perception factors. We grouped these attributes in five different categories: individual flood experience, socio-economic characteristics, demographics, distance to flood hazards (exposure) and reputation and related trust into messenger. We extracted the most important findings per category and summarised them.

2.3. Analysis of warning elements

We developed the categorisation into the three components – content, format and communication channel – to best suit our research scope, focusing specifically on the building blocks of the warning message itself. We analysed all articles resulting from the PRISMA review to identify the individual alternatives for each component, which represent the elements. We recorded each occurrence of each element, and identified whether it concerned a study that concluded in favour or against adopting the element for the creation of flood warnings. Furthermore, we collected reports of elements that were neutral, provided insights, suggested conditions for element adoption or suggested combinations of elements to be used. We established the prominence of elements by counting the number of mentions among articles. We established the "net" positive effect of elements by calculating the difference between number of articles with a positive and negative conclusion.

3. Results

3.1. Literature meta-analysis

Full results from the literature review depicted in Fig. 1 are provided in Table A.1 of the Appendix. These data are summarised in Fig. 2.

Between 2000 and 2015 the number of articles rose, and then stabilised (Fig. 2). Over 80% of articles focussed on industrialised countries in Europe, North America and Oceania (Fig. 2). In addition, the majority

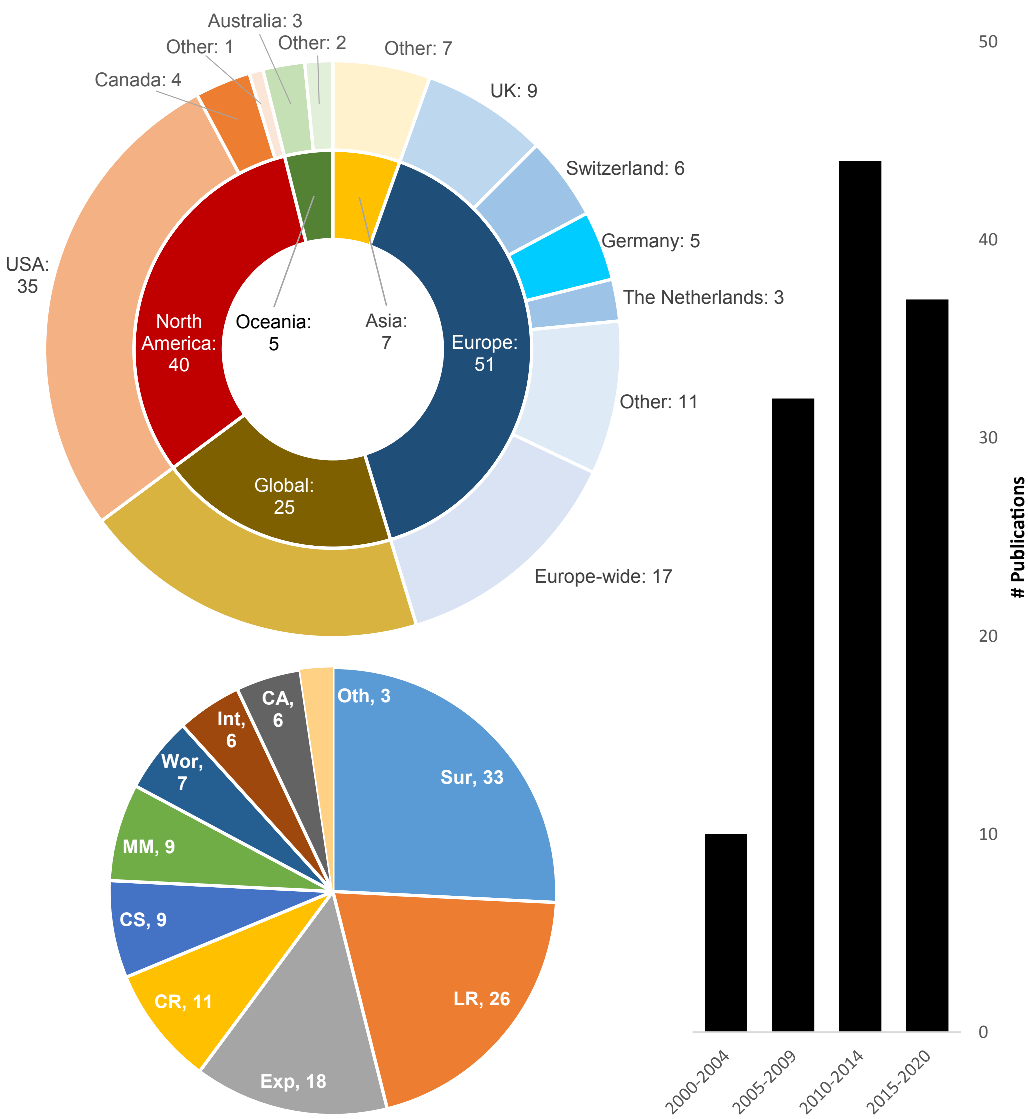

Fig. 2. Literature review meta-data. Top left: geographic distribution of research focus; the inner and outer circle represent the continent and country, respectively. Bottom left: distribution of articles according to their core methodology, Legend: Sur (Survey), LR (Literature Review), Exp (Experiment), CR (Content Review), CS (Case Study), MM (Mixed Methods), Wor (Workshop), Int (Interview), CA (Content Analysis), Oth (Other). Right: publication of articles over time (Excludes papers added during the peer-review process, as they did not appear in the database search).

of remaining articles were reviews with global focus, but results taken mostly from industrialised countries. Only seven articles focused on Asia (5.6%) and none focused on South America or Africa. Of the research articles, by far the most popular data gathering method used were surveys, followed by experiments (Fig. 2). Subjects of surveys were usually the public in a specific geographic context, while experiments were often conducted with students.

3.2. Attributes affecting flood risk perception

A significant body of literature explored risk perception related to natural hazards, covered by three recent reviews. Wachinger et al. (2013) argued that the process of shaping risk perception is influenced by four groups of factors, related to: 1) the type and severity of the natural hazard, 2) the source and amount of information received, 3) personal and cultural attributes such as age, gender and religion and 4) context, such as closeness to hazard and community size. O'Neill et al. (2016) found that (often incorrectly) perceived flood exposure, rather than actual exposure, determines flood risk perception. This tendency depended on cognitive, behavioural, socioeconomic and geographical factors. Most recently, Lechowska (2018) pointed to the uncertainty of the mechanisms behind risk perception formation, exposing the varying levels of clarity and knowledge in the research community regarding the effect of different factors. For the purpose of creating effective flood risk communication, we present the most significant personal attributes affecting risk perception (Table 1). These attributes are part of the background to the warning development cycle (Fig. 4).

3.3. The elements of flood warning communication

Fig. 3 presents an overview of the elements of flood warning communication. The results for the components content, format and channel are presented in Tables 2–4, respectively. The process of selecting and combining these elements is the backbone of the warning development cycle (Fig. 4). The most important elements of content for warning messages include the source of the warning, the nature, location and time of the hazard and recommended action (Table 2). While there was little disagreement between studies on these and most other elements of content, there was some disagreement regarding uncertainties. Although transparency concerning the inherent uncertainty associated with a flood risk (e.g., likelihood of occurring, severity and timing) were often associated with increased understanding, some studies highlighted the complexity associated with interpreting such information (Mileti et al., 2004; Shanahan et al., 2019; Spiegelhalter and Riesch, 2011), inhibiting improvement of response measures taken by recipients.

Table 1
Attributes analysed for their effect on flood risk perception relevant for flood warning communication, with reference to empirical studies. Ordered by number of studies, mentioned between brackets next to the attribute. **Bolded**: attributes shown to influence risk perception.

Attribute (#)	Findings	References
Flood experience (12)	Experience with floods increases risk perception, particularly when it concerns personal experience.	Armaş and Avram (2009), Baan and Klijn (2004), Botzen et al. (2009), Botzen and van den Bergh (2012), Grothmann and Reusswig (2006), Kellens et al. (2011), Keller et al. (2006), Terpstra (2011), Thistlethwaite et al. (2018), Turner et al. (2014)
	Risk perception remains strong for longer after an event when the memory is triggered (e.g., through confrontation with stories from affected people and the installation of physical flood commemoration signs).	Bradford et al. (2012), Wagner (2007)
Socioeconomics(e.g., education, income) (9)	Income, wealth and education have no or very little effect on risk perception, although it can affect understanding of different communication formats.	Armaş and Avram (2009), Baan and Klijn (2004), Botzen et al. (2009), Kellens et al. (2011), Miceli et al. (2008), Poussin et al. (2014), Terpstra (2011), Thieken et al. (2007), Thistlethwaite et al. (2018)
Distance of residency to flood hazard (6)	Residents closer to flood-prone areas show stronger risk perception than those who consider themselves distant from the hazard.	Bera and Daněk (2018), Botzen et al. (2009), Kellens et al. (2011), Miceli et al. (2008), O'Neill et al. (2016), Zhang et al. (2010)
Demographics (5)	Age positively correlates with experience and knowledge about hazards. Younger people are more likely to underestimate the risk.[a] Gender can correlate with preferences for warning elements.[b]	[a] Armaş and Avram (2009), Feldman et al. (2016), Karanci et al. (2005), Kellens et al. (2011) [b] Hayden et al. (2007)
Reputation & Trust (4)	Trust in authorities is a strong predictor for risk perception. Reputation and trust, affect people's interpretation of an agency's response to disasters.	Heitz et al., 2009; López-Vázquez and Marván, 2003; Terpstra, 2011; Terpstra et al., 2009; Wachinger et al., 2013

Besides decisions on the type of elements, the order in which information are presented also affects the interpretation of a warning. Bean et al. (2015) and Sutton and Kuligowski (2019) suggest the following order of content: source, hazard, location, time and guidance. This reflects the prominence of elements as reported in the body of literature (see ordering of Table 2). Notably, including a source is mentioned most often, and literature suggests that a recipients' preparedness to act largely depends on the perceived credibility of this (e.g. Bean et al., 2016; Turner et al., 2014).

In contrast to the academic consensus around the content of flood warnings, there was considerable disagreement between the findings of different studies on the formatting of messages (Table 3). Writing and graphics were most commonly identified as effective warning formats. Additionally, combining these elements increased their individual effectiveness (Hogan Carr et al., 2016; Lipkus, 2007; Savelli and Joslyn, 2013). Using affective writing tended to increase warning effectiveness (Perreault et al., 2014; Shanahan et al., 2019). Indeed, images appeared more effective than any other type of graphics, as they evoke emotional engagement (Dobson et al., 2018; Keller et al., 2006; Wagner, 2007).

Flood maps were subject to the greatest contradictions between studies (Table 3). Advances in location and cartographic design make flood maps an increasingly effective flood warning format (Dransch et al., 2010; Henstra et al., 2019). However, study subjects often appeared unable to understand a map, or locate themselves on one during an emergency (Liu et al., 2017). Therefore, designing maps containing appropriate information density and complexity is a delicate balancing act for practitioners issuing warnings. To assist map design, several authors evaluated users' information perception from flood maps (Fuchs et al., 2009; Luke et al., 2018; Van Kerkvoorde et al., 2018). They suggested an extensive list of best practices for cartographic design on e.g., legend position and composition, graphical differentiation between areas that are at risk and other areas and map scale (Fuchs et al., 2009; Henstra et al., 2019; Meyer et al., 2012).

Studies disagreed on the benefit of using probabilistic information such as likelihood of the predicted event. In addition, the most appropriate format of probabilistic information was contested, e.g., percentages, fractions, odd-ratios and return periods (Keller et al., 2006; LeClerc and Joslyn, 2012; Visschers et al., 2009). Communicating probabilities created misunderstanding among certain audiences that interpreted information heuristically instead of systematically. Moreover, correct interpretation depended on education level and the format of presentation, as graphical representations were understood better than numerical ones (Kashefi, 2009; Visschers et al., 2009). Differences in the outcomes of studies examining the effect of probabilities could be

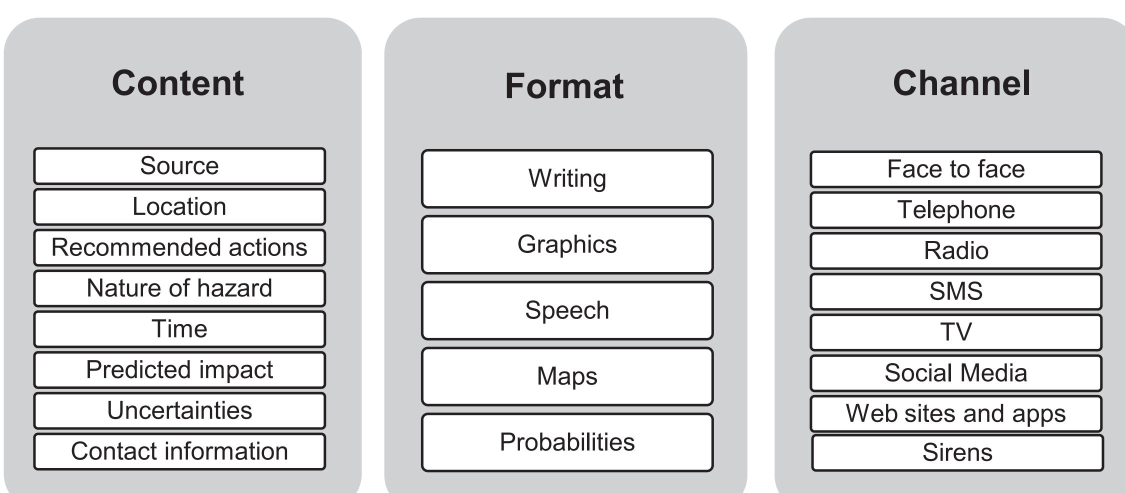

Fig. 3. Components (grey blocks) and corresponding elements (white rectangles) of flood warning messages.

Table 2
Elements of risk warning communication for the **Content** component. Column “Element”: (number) refers to the “net” positive effect (net support) of including this element in a warning (positive minus negative mentions in “Findings” column). The table is ordered by descending number of this net positive effect. Column “Findings”: ✓ or ✗ (number) refers to the total number of studies indicating positive or negative effect of including corresponding element respectively, 💡 (number) refers to the total number of reports of elements that were neutral, provided insights, suggested conditions for element adoption or suggested combinations of elements to be used. Comparison between elements are reported under all three classifications. Such study outcomes are reported either under both elements, or only under the most relevant element.

Element (net support)	Findings		References
Source (11) *Who sent message.*	✓11	Warnings from a trusted, credible and official source are most effective.[a] Effective flood warnings require trust in the authorities providing the warnings.[b]	[a] Bean et al. (2016), Liu et al. (2015), Pornpitakpan (2004), Stephens et al. (2013), Sutton et al. (2018), Sutton et al. (2014), Turner et al. (2014), Vieweg et al. (2010), Vihalemm et al. (2012), Wachinger et al. (2013) [b] López-Vázquez and Marván (2003)
Location (9) *Geographic information on hazard (incl. recipients’ location).*	✓9	Warnings should specify the exact location of the impending hazard. Recipients should be enabled to easily determine whether they are in the hazard location.	Bean et al. (2016), Bean et al. (2015), Fielding et al. (2007), Hogan Carr et al. (2016), King (2008), Mileti and Peek (2000), Sutton et al. (2014), Vieweg et al. (2010), Zhang et al. (2004)
Recommended actions (8) *Appropriate responses from recipients to reduce risk.*	✓8	People cannot be assumed to know the appropriate course of action.[a] Including recommended actions in warnings significantly affects both perception and response, rendering warnings overall more effective.[b]	[a] Mileti and Peek (2000) [b] Frisby et al. (2014), Lindell and Perry (2003), Mayhorn and McLaughlin (2014), Scolobig et al. (2018), Sellnow and Sellnow (2010), Sutton et al. (2014), Thieken et al. (2007)
Nature of hazard (7) *Type of hazard (e.g., flash flood) and why it is occurring.*	✓7	Effective warnings describe the nature of the hazard and explain its danger in sufficient detail to be acted on.	Dallo et al. (2020), Lindell (2018), Mayhorn and McLaughlin (2014), Mileti and Peek (2000), Sutton et al. (2014), Taylor et al. (2018), Wood et al. (2015)
	💡1	The marginal benefit of extra information on the nature of a hazard decreases.	Mu et al. (2018)
Time (4) *Start and duration of event, and recommended timing of action.*	✓4	Start and duration of the expected hazard as well as recommendations on when to start and finalise protective action should be included with each warning.	Demeritt et al. (2007), Mayhorn and McLaughlin (2014), Sutton et al. (2014), Taylor et al. (2018)
Predicted impact (3) *Impact-based warnings with information about the potential consequences (e.g., damage and disruption).*	✓4	Including an estimate or reference providing information on the severity and consequences of the flood hazard increases the likelihood of appropriate action by recipients.	Keller et al. (2006), Morss et al. (2018), Scolobig et al. (2018), Sutton and Woods (2016)
	✗1	In certain cases, where unclarity about appropriate action remains, impact-based warnings led to worse outcomes.	Potter et al. (2018)
	💡1	As impact-based warnings are increasingly applied, practitioners see challenges (e.g., data needs, verification, potential confusion, increased burden, design for individuals or society) and opportunities (e.g., improved public understanding, reduced false alarms, improved communication between agencies, added awareness)	Potter et al. (2021)
Uncertainties (3) *Likelihood of hazard occurring and range of possible severity levels.*	✓6	Uncertainty information increased understanding and produced overall better responses.	Fischhoff and Davis (2014), Frick and Hegg (2011), LeClerc and Joslyn (2015), Nadav-Greenberg and Joslyn (2009), Ramos et al. (2013), Stirling (2010)
	✗3	Uncertainty information decreased comprehension and did not produce different responses.	Mileti et al. (2004), Shanahan et al. (2019), Spiegelhalter and Riesch (2011)
	💡1	Uncertainty information presented in a graphical form was understood faster than in table form.	Marimo et al. (2015)
Contact information (2) *Who to contact for more info.*	✓2	Warnings should contain information that enables recipients to contact the warning source, or other appropriate authority, to obtain additional information or assistance.	Lindell and Perry (2003), Mayhorn and McLaughlin (2014)

explained by the audience’s level of education, their understanding of probabilities and experience with probabilistic forecasts (Strathie et al., 2017; Visschers et al., 2009).

The most effective channels were those that relied predominantly on the speech format (Table 4). This might be because spoken messages are more easily understood, personal and indicate a sense of urgency (Lamb et al., 2012; Turner et al., 2014). Widely studied in the UK, warnings delivered face-to-face were proven highly effective, evoking a high sense of urgency. As the most personal communication channel, it is resource intensive (Turner et al., 2014). While the UK has a longstanding and community-supported flood warden scheme by the Environmental Agency (Nagarajan et al., 2012), the effectiveness of face-to-face warnings in different contexts might vary. Besides formally organised face-to-face warning systems, informal warning systems also play an important role, particularly in the Global South (e.g., Parker and Handmer, 1998). Although the importance of such systems cannot be overestimated, we chose not to include such warning systems in our framework, which focuses on formal warning systems that can be adopted by authorities.

Next highest net support was found for two other channels that are highly dependent on speech: telephone and radio. Telephone can refer to pre-recorded mass-distributed messages or interactive flood lines, both accessible by landlines as well as mobile phones. Advantages of both telephone and radio include relatively high accessibility and affordability, rendering these channels low-cost and high-reach (e.g., Perreault et al., 2014). Another advantage of telephone was its potential to provide additional, tailored information to recipients if required (Liu et al., 2015; Turner et al., 2014). A limitation of radio was that messages cannot be repeated on demand. To be effective, warnings should therefore be repeated with high frequency (Liu et al., 2015).

The low level of net support for SMS was in contrast with the widespread application by agencies worldwide (Perera et al., 2019), such as the US federal emergency management (Bean et al., 2015; Potter et al., 2018), Swiss National Weather Agency (Weyrich et al., 2018) and the Meteorological Service of New Zealand (Potter et al., 2018). Possible explanation for the low net support is a general underrepresentation in literature from the past two decades, as it was deemed a proven and effective written warning channel (Sutton and Kuligowski, 2019).

Table 3
Elements of risk warning communication for the **Format** component. For an explanation of the symbols and structure of the table, see Table 2. Further explanation "Element": When an element occurs more than once, a sub-element is provided below. The bracketed numbers behind the element and sub-element (#) refer to their respective net positive effect.

Element (net support)	Findings		References
Writing (8): General (4) *Any warning that is in written form.*	✓5	Text warnings using imperative and directive language, bolded text and colour, received increased attention and are better understood than purely visual warnings.[a] Longer warnings (380 characters) resulted in better outcomes than shorter warnings (140 characters).[b]	[a] Dallo et al. (2020), Lamb et al. (2012), Sutton et al. (2014), [b] Bean et al. (2016), Sutton et al. (2018)
	✗1	Written evacuation orders were less reliable, trustworthy and clear compared to orders delivered in person.	Lamb et al. (2012)
	💡2	Writing should be combined with graphics and/or maps. Writing should provide concise explanation, while graphics should provide a quick visual of the risk.	Dallo et al. (2020), Hogan Carr et al. (2016)
Writing (8): Affect (4) *This sub-type refers to text that aims to evoke emotional responses from the reader.*	✓5	Emotional language is more effective at altering risk perception than neutral, matter-of-fact language.	de Moel et al. (2009), De Wit et al. (2008), Keller et al. (2006), Rashid (2011), Shanahan et al. (2019)
	✗1	In an experimental setting, neutral warning messages were perceived as more credible than those intentionally inducing fear.	Perreault et al. (2014)
Graphics (8) General (2) *Any format which uses a type of graph or visualisation, image, or photograph.*	✓4	Graphics such as pictograms, influence individual risk perception and increased understanding of uncertainties.[a] Graphics were the fastest and most effective way to transfer information to recipients.[b]	[a] Ash et al. (2014), Dallo et al. (2020), Lipkus and Hollands (1999) [b] Hogan Carr et al. (2016)
	✗2	Graphics bore a higher risk of misinterpretation than writing.	Lipkus (2007), Savelli and Joslyn (2013)
	💡3	Numeracy levels determined the ability to understand graphics.[a] If used, warnings should combine graphics and writing, where graphics provide a visual overview and a short text provides more detail.[b]	[a] Spiegelhalter and Riesch (2011) [b] Dallo et al. (2020), Hogan Carr et al. (2016)
Graphics (8) Images (6) *This sub-type refers to photographs.*	✓6	Photographs depicting past floods and their impacts enhanced warning compliance, accuracy of risk estimation, risk perception and the willingness to reduce the risk.	Burnside et al. (2007), de Moel et al. (2009), Keller et al. (2006), Luke et al. (2018), Schirillo and Stone (2005), Wagner (2007)
	💡1	Images impact is highest when depicting locally known areas.	Wagner (2007)
Speech (2) *Any format which uses verbal information.*	✓2	Spoken warnings were considered more reliable and trustworthy, thus increasing the probability of households taking protective action.	Lamb et al. (2012), Turner et al. (2014)
	💡1	To minimise the risk of misinterpretation, verbal and numerical information should be combined.	Budescu et al. (2014)
Flood maps (1) *Any format which includes the use of a map.*	✓5	Flood maps improved warning effectiveness and comprehension, given they contain enough detail for recipients to locate themselves relative to the hazard.	Dallo et al. (2020), Dransch et al. (2010), Kellens et al. (2009), Lieske (2012), Liu et al. (2017)
	✗4	Hazard information presented on a map was less understandable than when presented graphically or in a table.[a] Self-location on, and comprehension of maps was problematic, especially in emergencies.[b]	[a] Dobson et al. (2018) [b] Akella (2009), Bean et al. (2016), Lindell (2018)
	💡7	Cartographic best practices should be followed: Clear background and clear contrast to informative elements in centre of the map. Title above the map, close to the legend. Mark hazard in shades of red, in decreasing order. Include local area names or landmarks to aid self-location.[a] Key challenges for map development are professional and institutional divides and knowledge gaps. Key challenge for use is navigating on a map.[b] Maps should be used in combination with writing.[c]	[a] Dransch et al. (2010), Fuchs et al. (2009), Meyer et al. (2012), Van Kerkvoorde et al. (2018) [b] Nones (2017), Henstra et al. (2019) [c] Dallo et al. (2020)
Probabilities (0) *Any warning using a probabilistic format. This is in contrast to deterministic warnings, which do not provide a measure of the associated uncertainty.*	✓2	Probabilistic warnings provided extra information helping users to make better decisions compared with deterministic forecasts.	Joslyn et al. (2007), Verkade and Werner (2011)
	✗2	Warnings containing probabilistic information were poorly understood.	Kashefi (2009), Visschers et al. (2009)
	💡6	To minimise misinterpretation, combining verbal and numerical formats have shown to be promising.[a] Probabilities presented in the format "percentage chance per year" were best understood.[b] Risk perception was greater when cumulative probabilities over time where used instead of the probability of a single event.[c]	[a] Budescu et al. (2014) [b] Bell and Tobin (2007), Waylen et al. (2011) [c] LeClerc and Joslyn (2012), Keller et al. (2006), Strathie et al. (2017)

Contrarily, social media were widely researched as a warning channel over the past two decades. Conclusions about their effectiveness varied and were found context dependent (Table 4). Recent research indicated a significant demand for flood warnings disseminated via social media (Cho et al., 2013; Morss et al., 2018; Stephenson et al., 2018), although presumably skewed towards the younger population (Taylor et al., 2018). Social media are particularly prone to the spread of misinformation due to their democratic access, which is in principle a good feature, but may compromise their reliability for risk communication (e.g., Lovari and Bowen, 2020). This tendency increases the responsibility of emergency management to refute misleading content and provide accurate information on this channel.

The effectiveness of web sites and applications was highly contested. They were often considered ineffective because of their inaccessibility (e.g., Lam et al., 2017; Rohrmann, 2004). For example, questionnaire interviews with over a thousand residents of Hong Kong showed that recipients were reluctant to visit a website to acquire warning information (Lam et al., 2017). However, a comprehensive review on early warning system practices reports this channel to be the most commonly used around the world (Perera et al., 2019). These findings align with

Table 4
Elements of risk warning communication for the **Channel** component. For an explanation of the symbols and structure of the table, see Tables 2 and 3.

Element (net support)	Findings		References
Face-to-face (6) General (3) *Any warning communicated in person.*	✓3	Face-to-face warnings significantly enhanced preparedness to take protective action, particularly compared to warnings disseminated through mass media.[a] Older generations reported a comparatively strong preference for this channel.[b]	[a] Moser (2010), Turner et al. (2014) [b] Parker et al. (2009)
Face to face (6) Flood wardens (3) *Personal dissemination of warnings across a community, often via door knocking.*	✓3	Flood wardens enabled bi-directional information transfer, improving decision-making around an incumbent hazard. Personal warnings transmitted a greater sense of urgency and authority, making recipients more likely to follow recommended actions.	Höppner et al. (2012), Ping et al. (2016), Turner et al. (2014)
	💡2	Flood wardens cascaded warnings through local communities. This required well-trained personnel, sufficient lead-time and community support.	Nagarajan et al. (2012), Ping et al. (2016)
Radio (4) *Any spoken warning that utilises AM or FM radio broadcasts.*	✓4	Radio was the most popular source for flood warnings in a survey of Australian households.[a] Elderly residents reported radio and TV as their preferred channel.[b]	[a] Cretikos et al. (2008), Dallo et al. (2020), Parker et al. (2009) [b] Lam et al. (2017)
	💡1	Radio broadcasts can provide localised warnings. They should be repeated often, with timely updates on the hazard.	Höppner et al. (2012)
Telephone (3) *Any spoken warning that utilises telephone connections (wired or mobile) to disseminate flood warning information.*	✓3	Flood hotlines, or "flood-lines", can playback recorded flood warnings and forward callers to a call centre where they can speak to an expert and receive more information. Successfully used in the UK, where it was the main channel to receive flood warnings.	Pal and Ghosh (2017), Parker (2004), White and Howe (2002)
TV (3) *Any warning that is broadcast on TV networks.*	✓5	TV was the preferred channel for receiving hazard warnings according to household surveys in Switzerland, Bangladesh, USA and Australia.[a] Elderly residents in Hong Kong and USA reported radio and TV to be their preferred channel of risk communication.[b]	[a] Cretikos et al. (2008), Dallo et al. (2020), Fakhruddin et al. (2015), Hayden et al. (2007) [b] Lam et al. (2017)
	✗2	Canadian households ranked TV the least preferred channel.[a] In poorer or remote areas such as South- and East Asia, access to TV is limited.[b]	[a] Silver (2015) [b] Keoduangsine and Goodwin (2012)
	💡1	Three broadcasts between 7 pm and 9 pm, reaching 50% of the TV audience, with a lead-time of one day, showed to be an effective approach in for flood warning China.	Wei et al. (2010)
SMS (2) *Any written warning that is transmitted via cell phone networks to users' mobile phones.*	✓2	SMS was the preferred channel in a survey of Canadian households.[a] SMS warnings were effective where internet access is limited and when contact details are provided to where individuals can get more information.[b]	[a] Silver (2015) [b] Höppner et al. (2012)
	💡1	Multiple messages can be linked to circumvent size limits, which was found more effective than a single message.	Sutton et al. (2018)
Social media (1) *Any warning that is transmitted via social media applications. Due to the significant communication capabilities between social media and web sites and applications, the two elements are kept separate. Social media typically utilises specific platforms that are often accessed via mobile phone applications.*	✓5	Studies from Japan and Ireland, among others, confirmed that the public, especially youth, actively seek information on hazards via social media.[a] As information was more likely to be forwarded when coming from an official sources, relevant authorities need to establish social media presence.[b] Social media usage was overall viewed as beneficial by emergency communication professionals during floods in South Carolina, enabling two-way communication.[c]	[a] Cho et al. (2013), Lam et al. (2017) [b] Morss et al. (2016), Stephenson et al. (2018) [c] Lovari and Bowen (2020)
	✗4	Access to social media varied by socioeconomic background. It is therefore not a reliable channel to reach an entire population. Agencies often lack the resources to maintain social media channels. Surveys in Switzerland showed low preference for social media.	Alexander (2014), Dallo et al. (2020), Feldman et al. (2016), Flizikowski et al. (2014),
	💡2	A lack knowledge and skills needed to employ social media by flood warning issuing authorities was the main barrier for its application, concluding from a survey of the population in Australia.[a] Best practices for effective social media warnings: Use capitalisation to increase urgency, specifically mention hazard type and location, provide instructions for protective action and use visual elements to aid comprehension.[b] Social media can help rapid dissemination as well as collection of data, but should not go at the cost of using traditional media. Agencies should be aware of the role of misinformation.[c]	[a] Ehnis and Bunker (2012) [b] Sutton and Kuligowski (2019) [c] Lovari and Bowen (2020)
Web sites and applications (0) *Any flood warning that is presented on websites or applications accessible through devices connected to the internet (e.g., pc, tablet and mobile phone).*	✓4	Younger members of the public in Australia and the USA expressed a need for online risk communication.[a] The internet if available to most, democratises access to hazard information.[b] If integrated in a general-purpose app (e.g., weather app) or multi-hazard app, hazard warning apps are useful to reach a large audience and serve as a first entry point to authorities, while offering interactive features.[c]	[a] Lindell and Perry (2003), Rohrmann (2004) [b] Mills and Curtis (2008) [c] Dallo and Marti (2021))
	✗4	Surveys from Canada, the USA and Hong Kong indicated internet as one of the least preferred channels for risk communication.[a] In poorer or remote areas, internet access was limited.[b]	[a] Hayden et al. (2007), Lam et al. (2017), Silver (2015) [b] Keoduangsine and Goodwin (2012)
Flood sirens (0)	✓3		

(*continued on next page*)

Table 4 (*continued*)

Element (net support)	Findings		References
Devices emitting alarm sounds.		Sirens are low-cost and can capture the attention of most residents in a specific area. Respondents of surveys in Europe, Canada and the USA repeatedly favoured sirens as an emergency communication channel.	Hayden et al. (2007), Höppner et al. (2012), Silver (2015)
	✗3	Without prior knowledge, sirens were misunderstood or confusing. This effect was mitigated by on-the-ground personnel, providing additional information regarding the hazard.	Fakhruddin et al. (2015), Höppner et al. (2012), Woody and Ellison (2014)

the increasing importance of mobile applications for hazard communication (Tan et al., 2017). Indeed, websites and mobile apps appear to be useful in providing additional detailed information to other warning channels, such as SMS or social media (Dallo and Marti, 2021).

Finally, the effectiveness of sirens was also contested. Although easy to install and maintain, sirens cannot transmit complex information. Therefore, their effectiveness depends on the availability of prior knowledge on appropriate responses in the population (Fakhruddin et al., 2015). Most scholars agreed that sirens are only effective when paired with a channel that can transmit information that is more detailed, such as on-the-ground flood wardens and radio (Fakhruddin et al., 2015; Hayden et al., 2007; Höppner et al., 2012; Woody and Ellison, 2014).

Given the popularity and scientific evidence supporting the use of channels that depend on speech (e.g., radio, TV, face-to-face; see Table 4), the lack of research on the speech format is remarkable (Table 3). A possible explanation could lie in the complexity of empirically testing spoken communication formats (Feldman et al., 2016).

3.4. *Quality criteria for flood warning development*

Selecting the right combination of content, format and dissemination channel for flood warnings is critical in order to evoke desired behavioural responses from targeted audiences. Besides deciding on the *type* of elements, certain guidelines considering their *quality* should be observed. Quality criteria are part of the background to the warning development cycle (Fig. 4). Most importantly, warnings should:

- **Be specific.** Specific and brief warnings are most effective (Bean et al., 2015). Warning development is a balancing act to make messages short enough for quick comprehension, but covering all essential information (Bean et al., 2015; Hagemeier-Klose and Wagner, 2009; Sutton et al., 2014).
- **Use appropriate language.** A study from the USA concluded that a common flood risk management language was lacking between emergency managers and scientists (Wood et al., 2012). Personal attributes such as age and education level affect how warnings are understood and interpreted. Non-technical language and local jargon can increase the reach of warnings among different communities (Perić and Cvetković, 2019). Particularly when quick decision-making is required from recipients, the complexity of warnings language should be reduced (Doksaeter Sivle and Kolstø, 2016). Language should be tailored to the targeted audience, as for example a "100-year flood" is understood very differently between scientists and the public (Bell and Tobin, 2007; Hagemeier-Klose and Wagner, 2009). Furthermore, language can be perceived as positive or negative, and even induce fear. Although alarmist language can trigger certain (desired) behaviour, the opposite effect is observed in the absence of clear directions and recommended actions (Nerlich et al., 2010). Provoking fear, while effective in certain circumstances, may induce fatalism, paralysis or sensationalism (O'Neill and Nicholson-Cole, 2009; Perreault et al., 2014).
- **Be transparent.** Warnings should clearly outline what is known, what remains unknown and what is uncertain. The level of transparency translates to the level of trust and perceived credibility of a message and its source (Höppner et al., 2012; Sutton et al., 2014). Uncertainty should be explained in conjunction with recommendations for action (Lundgren and McMakin, 2009). Transparency is closely related to trust in the message and its source, which plays a vital role in warning effectiveness (Terpstra, 2011; Wachinger et al., 2013).
- **Be consistent.** Warnings should be consistent, but clear about changes to the hazard. All different sources of communication should align their communication strategy and content (Mileti and Peek, 2000; Weyrich et al., 2019).

4. Discussion

4.1. *Creating effective warnings*

The warning development cycle is generally triggered when a forecast from meteorological/hydrological services exceeds a certain critical threshold. Such forecasts are often produced on a daily basis and represented by the forecast cycle in Fig. 4. Warning development then commences, selecting from 21 elements identified between the three components of flood warning messages: eight elements of content, five of format and eight of channel (Fig. 3). This process can be either (partly or fully) automated in the FEWS, or manual. When automated, a warning system has been set up in advance to select a combination of elements that best fit an exceeded trigger level from a forecast. Theoretically, any number of elements from each component could be combined to create a warning, resulting in $(2^8-1)\bullet(2^5-1)\bullet(2^8-1) \approx 2.0\text{million}$different options (note that this number inflates exponentially with additional elements). Although many of these combinations are practically impossible or undesirable (e.g., sending an image over the radio), emergency managers are faced with a broad pallet of alternatives. Tables 2–4 provide insights to narrow down the options by presenting the evidence available in literature for and against using different elements. However, it should be noted that the effectiveness of warnings is highly context-dependent (Höppner et al., 2012; Keoduangsine and Goodwin, 2012; Taylor et al., 2018). The "net support" for different elements presented in Section 3.3 should therefore not be considered a universally valid ranking.

Firstly, shortly incumbent and severe flooding requires immediate action from the population, making specific elements better suited. For example, warnings disseminated through sirens are immediately received by large parts of the population, while written newspaper articles result in a delayed and potentially smaller reach (Fakhruddin et al., 2015). Secondly, farmers from a rural community without fast internet connections are more effectively reached by SMS, radio or flood wardens, while the population of a modern city can be reached by a diverse set of channels, including those requiring the internet. Thus, context defines desirable choice of elements through the characteristics of: (1) the impending hazard, including the lead-time and severity and (2) the location (e.g., Keoduangsine and Goodwin, 2012; Lam et al., 2017; Mu et al., 2018). Additionally, the availability and preferences for communication technology, both for the sender and receiver of the warning, define the choice of elements (Keoduangsine and Goodwin, 2012; Lam et al., 2017; Mills and Curtis, 2008; Stephens et al., 2013; UNISDR, 2015). Together, these considerations of contexts are part of the background to the warning development cycle (Fig. 4).

The attributes of risk perception, discussed in Section 3.2, further shape the choice of elements. For example, past exposure to floods affects current risk perception of a population (Wood et al., 2012). Lack of experience with floods is associated with an underestimation of risk (low risk perception) and limited understanding on appropriate responses, exacerbating flood impact (Bera and Daněk, 2018; O'Neill et al., 2016). Similarly, providing references to previous floods (in warning messages as well as physical references such as flood markers on buildings) keeps risk perception higher for longer (Bradford et al., 2012; Wagner, 2007). Trust, as another example of an attribute of risk perception, enhances warning effectiveness. Adding a reference to a trusted organisation in a warning message may therefore improve the warning, while the opposite would be achieved when the referenced source lacks public trust (Heitz et al., 2009; López-Vázquez and Marván, 2003; Terpstra, 2011; Wachinger et al., 2013).

Once the content, channel and format are determined, a drafted warning should adhere to best practice as outlined in the quality criteria of Section 3.4. As emphasised throughout this review, these guidelines, the attributes of risk perception and the context interplay with one another, constituting the background and framework within which the warning is crafted (Fig. 4). As the channel is most constrained because of its dependency on available technology and infrastructure, it can serve as the entry point to the warning development cycle. However, this process should not be linear, and multiple cycles of changes and adjustments to the elements of warnings can be made for refinement. Höppner et al. (2012) even argue to open up such cycles via two-way communication strategies, in order to elicit the informational needs of specific groups and tailor the risk communication approach. After every cycle, the drafted warning is evaluated to fulfil all contextual and quality criteria, before it is dispatched to the target audience (Fig. 4). Finally, lessons can be drawn from evaluating the effects of the disseminated warning in practice (warning dissemination cycle) to improve warning development in subsequent emergency situations (Mayhorn and McLaughlin, 2014).

In contexts that use (semi-) automated warning systems, such as the IPAWS system in the USA (Bean et al., 2015), several parts of the stylised warning development process from Fig. 4 are performed as part of the development and consecutive refinements of such system. For example, depending on the severity of the forecasted flood, a system might either simply depict the risk on a map online (low severity) or send a SMS and push notification to all residents in a risk area (high severity). Here we provide a simple example to illustrate the non-automated warning development process as depicted in Fig. 4. The emergency management agency of a small African country receives information from the hydrological services about a forecast for extreme discharge within three days in a river with bordering agricultural land and villages in a rural area. The emergency managers know that to prepare the local residents and farmers, immediate warnings should be issued. As internet connections are limited in the area, but phone connections are good and widely used, they decide to select this channel for their warning. They want to inform the residents of the timing and exact location of the flood, as well as the possible consequences for the farmers (content). They decide to use both the format of SMS messages as well as to open a flood line providing a contact point for more information. Combining these contents and for all formats they create the warning. After evaluation, they conclude that the SMS is too long when including all the information. They therefore decide to limit the information to the timing and type of hazard, and add the contact details of the flood line to provide more information to those in need for it. They furthermore add the urgent request to inform any family members of the impeding flood, as not all elderly members of the community own a phone, but family ties are strong. After recreating the warning, they send the SMS out to the relevant communities.

4.2. Outlook

Research in hazard detection and risk warning communication is scattered across disciplines (e.g., hazard forecasting, risk analysis, behavioural psychology), applications (diverse set of natural and anthropogenic hazards) and domains (academic research, emergency management practice). To advance the field, transdisciplinary efforts are required to integrate and synthesise all relevant knowledge across academia and practice (Lang et al., 2012). This review is an attempt to do just that; draw from different disciplines (e.g., publications in hydrology, risk management and psychology) and applications (focus on flood warnings, but include other types warning implementation) to provide insights that help create more effective (flood) warnings. Further testing of academic findings (such as those from this review) in practical settings should be undertaken to assess their validity outside the controlled academic setting they stem from.

Such validation of the findings from this review was attempted by the authors. Undertaking this review was inspired by, and part of a larger project (FANFAR, 2021) focussing on co-development of a flood forecast and early warning system for West African countries (Andersson et al., 2020; Lienert et al., 2020a, 2021, 2020b). Systematic discussion of the implications of our findings with emergency managers of 17 countries in West Africa was planned and commenced as part of this project in a workshop in Abuja (Nigeria) in February 2020. We started with discussing different individual warning elements in isolation. We planned follow-up research including the assessment of different combinations of elements in complete warnings, and linking such warnings to different scenarios in terms of hazard type and context (preliminary results: Kuller et al., 2020). Unfortunately, this research effort was halted due to logistical problems and health risks posed by the global COVID-19 pandemic, prohibiting further personal interactions with our research colleagues and co-development participants.

Holding these types of systematic discussions and even implementing findings in real-world settings in Africa is even more important considering that this review largely reflects the state-of-the-art of knowledge and application in industrialised countries, with the bulk of available research coming from Europe, North America and Oceania. As emphasised before, risk communication is highly embedded in local contexts. This highlights the need to investigate the transferability of our findings to different contexts such as Africa, Asia and South America. Even within industrialised countries, research findings are occasionally skewed to specific geographies, as is the case for e.g., research on flood wardens in the UK. Therefore, we urge the research community to further explore transferability of our findings both to different contexts within industrialised countries and beyond.

This review concentrates on warnings for hydrological hazards, as the most frequent and impactful natural hazard worldwide. However, most findings are directly applicable to other types of natural, and even anthropogenic hazards. Psychological and behavioural mechanisms involved in the hazard-response cycle are universal and largely independent from the nature of the hazard. Hence, this review draws from research beyond the confines of the flood domain. Indeed, most of our findings regarding the elements of successful warnings can be extended outside the flood domain, acknowledging differences that might exist with other hazards regarding e.g., lead-times, geographic characteristics and desired response measures. Recognising the generic nature of warning communication, research attention is increasingly directed at integrating and streamlining hazard and warning communication through multi-hazard platforms (Dallo et al., 2020). Such platforms aim to present diverse hazards in a single location, adopting uniform content and formatting. Recent developments in information and communication technology provide interactive and intuitive user interfaces, enhancing a users' broad risk awareness and providing a one-stop shop for warning dissemination (e.g., ALERTSWISS app; online available at: https://www.alert.swiss/) They furthermore promote collaborative, two-way communication and sharing functions, deemed desirable to increase success (Ehnis and Bunker, 2012; Höppner et al., 2012).

The rise of multi-hazard platforms also sparks attention for the interplay between different warning elements, and the effectiveness of different sets of combinations. Traditionally, most research attention has

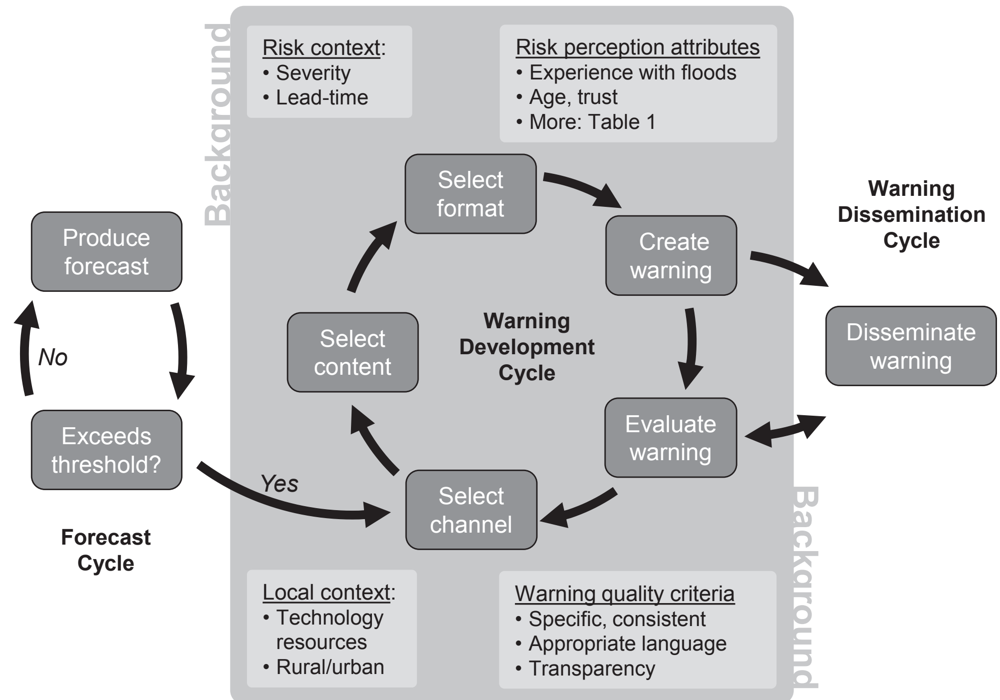

Fig. 4. Warning development process. Dark grey boxes: action steps in creation of flood warning. Light grey boxes: Factors influencing the decisions made in action steps of warning development cycle (background).

been directed at the effects of different elements in isolation, as reflected in Tables 2–4. Extrapolating the effect of individual elements in warnings containing combinations of those elements is problematic, considering the varying research approaches, contexts and subjects from individual studies. Although we have some insights into the combination of certain elements, such as different formats, or a format with a channel, little is known about the comparative effect of different constellations of elements that form a complete warning. Such knowledge is crucial, as in practice, warnings must always constitute a coherent ensemble of at least one piece of content, format and channel. Reciprocal interactions between elements could change findings regarding the effect of individual elements. Further complexity is added when considering the diverse possible implementation scenarios with varying context in terms of location, hazard type, severity and targeted populations. Systematic investigation of this complex interplay, depicted in Fig. 4, is required to move the field of risk communication forward.

While the increasingly accelerating advancements in technology uncover seemingly endless opportunities for risk monitoring, representation and distribution, both practice and academia struggle to keep up with this (Ash et al., 2014; Feldman et al., 2016; Henstra et al., 2019). New channels of communication become available to growing fractions of the population, while futuristic formats are mainstreamed at a high pace (e.g., real-time location tracking). An increased effort in development and testing of the novel tools at the disposal of emergency management is urgently needed. For example, the application of web-pages, apps and social media result in highly contradictory outcomes (Table 4), while the highest levels of agreement are concerned with formats and channels that are increasingly archaic and obsolete (Tables 3 and 4).

5. Concluding remarks

Providing early warnings are an effective way to mitigate the negative impacts of flooding. When developing Flood Early Warning Systems, a strong focus is generally put on the accuracy and reliability of the hydrological forecast. While accuracy is of great concern for obvious reasons, the importance of the quality of warning communication should not be overlooked. No matter the quality of the forecast, if this information fails to reach the relevant actors in a comprehendible and timely fashion, it is rendered useless. The effectiveness of a warning is determined by its capacity to evoke certain intended and desired behaviour among its recipients. This capacity, in turn, is the outcome of a complex interplay between its elements of content, format and channel. The generation of flood warnings should occur in the light of personal attributes of the target audience, such as demographics and experiences with past events. At the same time, warnings should be sensitive to the specific local contexts and forecast scenarios. The importance of a tailored approach cannot be overstated, as no one-size-fits-all exists. Indeed, while this review outlines the state-of-the-art in research on the effectiveness of all warning elements, the academic evidence presented to support or reject the effectiveness of individual elements should be appreciated in their specific context and integration with other elements. Nevertheless, our insights are crucial to shape and improve warning communication in the future. The framework provided in this paper comprises a clear overview of the known elements of food warnings, and a conceptual representation of their implementation in the development cycle of flood warnings. Other aspects informing this development include the risk context, local context, the attributes of risk perception and general warning quality criteria. To further research in flood warning development, future studies should explore the complex interplay of individual elements in real-world case studies, focussing beyond the context of industrialised countries.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was performed as part of a project aimed at developing a flood forecast and early warning system in West Africa called FANFAR (www.fanfar.eu). We thank the FANFAR consortium members, and especially the workshop participants in West Africa, hydrologists and emergency managers, for fruitful discussions about the importance of effective flood warning systems, and inspirations for this paper. Special thanks to Jafet Andersson, Francisco Silva Pinto and Daniel Hofmann for their valuable input on the content. Special thanks to Lorna Little for language checking and editing. This work was supported by the European Union's Horizon 2020 research and innovation programme under grant agreement No 780118. This research was further supported by the Eawag Discretionary Funding scheme to offset impacts of COVID-19.

Appendix. Raw results of the literature review

Citation	Year	Method(s)	Country	Continent
Dallo and Marti, 2021	2021	Workshops	Switzerland	Europe
Potter et al., 2021	2021	Interviews, Workshops	N/A	Global
Dallo et al., 2020	2020	Surveys	Switzerland	Europe
Lovari and Bowen, 2020	2020	Interviews	USA	North America
Henstra et al., 2019	2019	Literature review	N/A	Global
Perić and Cvetković, 2019	2019	Surveys	Serbia	Europe
Shanahan et al., 2019	2019	Experiments	USA	North America
Sutton and Kuligowski, 2019	2019	Literature review	USA	North America
Bera and Daněk, 2018	2018	Case studies	Czech Republic	Europe
Dobson et al., 2018	2018	Experiments	UK	Europe
Lindell, 2018	2018	Literature review	N/A	Global
Luke et al., 2018	2018	Workshops	USA	North America
Morss et al. 2018	2018	Surveys	USA	North America
Mu et al., 2018	2018	Experiments	UK	Europe
Potter et al., 2018	2018	Surveys	New Zealand	Oceania
Salman and Li, 2018	2018	Literature review	N/A	Global
Stephenson et al., 2018	2018	Content analysis	UK	Europe
Sutton et al., 2018	2018	Experiments	USA	North America
Taylor et al., 2018	2018	Literature review	N/A	Global
Thistlethwaite et al., 2018	2018	Surveys	Canada	North America
Van Kerkvoorde et al., 2018	2018	Surveys, Workshops	Belgium	Europe
Weyrich et al., 2018	2018	Surveys	Switzerland	Europe
Lam et al., 2017	2017	Surveys,Other	Hong Kong	Asia
Liu et al., 2017	2017	Experiments	USA	North America
Nones, 2017	2017	Content review	N/A	Europe
Pal and Ghosh, 2017	2017	Content review	India	Asia
Strathie et al., 2017	2017	Surveys	N/A	Europe
Bean et al., 2016	2016	Interviews, Workshops	USA	North America
Doksaeter Sivle and Kolstø, 2016	2016	Interviews	Norway	Europe
Feldman et al., 2016	2016	Surveys	USA	North America
Hogan Carr et al., 2016	2016	Workshops	USA	North America
Morss et al., 2016	2016	Surveys	USA	North America
O'Neill et al., 2016	2016	Literature review	N/A	Europe
Ping et al., 2016	2016	Case studies	UK	Europe
Sutton and Woods, 2016	2016	Workshops	USA	North America
Bean et al., 2015	2015	Literature review	N/A	Global
Fakkhrudin et al. 2015	2015	Case studies	Bangladesh	Asia
LeClerc and Joslyn, 2015	2015	Experiments	USA	North America
Liu et al., 2015	2015	Experiments	USA	North America
Marimo et al., 2015	2015	Surveys	UK	Europe
Silver, 2015	2015	Interviews, Surveys	Canada	North America
Alexander, 2014	2014	Literature review	N/A	Global
Ash et al., 2014	2014	Surveys	USA	North America
Budescu et al., 2014	2014	Surveys	N/A	Global
Fischhoff and Davis, 2014	2014	Literature review	N/A	Global
Flizikowski et al., 2014	2014	Surveys	N/A	Europe
Frisby et al., 2014	2014	Experiments, Content analysis	USA	North America
Mayhorn and McLaughlin, 2014	2014	Literature review	N/A	Global
Perreault et al., 2014	2014	Experiments	USA	North America
Poussin et al., 2014	2014	Surveys	France	Europe
Sutton et al., 2014	2014	Content analysis	USA	North America
Turner et al., 2014	2014	Surveys	Pakistan	Asia
Woody and Ellison, 2014	2014	Interviews	USA	North America
Cho et al., 2013	2013	Content analysis	Japan	Asia
Kellens et al., 2013	2013	Literature review	N/A	Europe
Ramos et al., 2013	2013	Experiments	N/A	Europe
Savelli and Joslyn, 2013	2013	Experiments	USA	North America
Stephens et al., 2013	2013	Surveys	USA	North America
Wachinger et al., 2013	2013	Literature review	N/A	Global
Bradford et al., 2012	2012	Surveys	N/A	Europe
Ehnis and Bunker, 2012	2012	Case studies	Australia	Oceania
Höppner et al., 2012	2012	Content review	N/A	Europe
Keoduangsine and Goodwin, 2012	2012	Content review	N/A	Global
Lamb et al., 2012	2012	Experiments	New Zealand	Oceania
LeClerc and Joslyn, 2012	2012	Experiments	USA	North America
Lieske, 2012	2012	Case studies	Canada	North America
Meyer et al., 2012	2012	Case studies	N/A	Europe

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Citation	Year	Method(s)	Country	Continent
Nagarajan et al., 2012	2012	Other	N/A	Global
O'Sullivan et al., 2012	2012	Surveys	N/A	Europe
Vihalemm et al., 2012	2012	Workshops	Estonia	Europe
Wood et al., 2012	2012	Case studies	USA	North America
Frick and Hegg, 2011	2011	Surveys	Switzerland	Europe
Rashid, 2011	2011	Content analysis	Canada	North America
Spiegelhalter and Riesch, 2011	2011	Literature review	N/A	Global
Terpstra, 2011	2011	Surveys	Netherlands	Europe
Verkade and Werner, 2011	2011	Case studies	USA	North America
Dransch et al., 2010	2010	Literature review	N/A	Europe
Moser, 2010	2010	Literature review	N/A	Global
Nerlich et al., 2010	2010	Literature review	N/A	Global
Sellnow and Sellnow, 2010	2010	Literature review	N/A	Global
Stirling, 2010	2010	Content review	N/A	Europe
Vieweg et al., 2010	2010	Content analysis	USA	North America
Wei et al., 2010	2010	Other	China	Asia
Zhang et al., 2010	2010	Surveys	USA	North America
Akella, 2009	2009	Surveys	USA	North America
Armaş and Avram, 2009	2009	Interviews	Romania	Europe
Botzen et al., 2009	2009	Surveys	Germany	Europe
de Moel et al., 2009	2009	Literature review	N/A	Europe
Fuchs et al., 2009	2009	Content review	N/A	Europe
Golding, 2009	2009	Case studies	UK	Europe
Heitz et al., 2009	2009	Surveys	France	Europe
Kashefi, 2009	2009	Surveys	UK	Europe
Kellens et al., 2009	2009	Literature review	Belgium	Europe
Nadav-Greenberg and Joslyn, 2009	2009	Experiments	USA	North America
Parker et al., 2009	2009	Content review	N/A	Europe
Terpstra et al. 2009	2009	Workshops	Netherlands	Europe
Visschers et al., 2009	2009	Literature review	Switzerland	Europe
Cretikos et al., 2008	2008	Surveys	Australia	Oceania
de Wit et al., 2008	2008	Experiments	N/A	Europe
King, 2008	2008	Surveys	Australia	Oceania
Miceli et al., 2008	2008	Surveys	Italy	Europe
Mills and Curtis, 2008	2008	Other	USA	North America
Bell and Tobin, 2007	2007	Surveys	USA	North America
Burnside et al., 2007	2007	Surveys	USA	North America
Demeritt et al., 2007	2007	Workshops	N/A	Europe
Fielding et al., 2007	2007	Case studies, Surveys	UK	Europe
Hagemeier-Klose, 2007	2007	Surveys, Workshops	Germany	Europe
Hayden et al., 2007	2007	Surveys	USA	North America
Joslyn et al., 2007	2007	Experiments	USA	North America
Lipkus, 2007	2007	Content review	N/A	Global
Thieken et al., 2007	2007	Interviews	Germany	Europe
Wagner, 2007	2007	Interviews, Surveys	Germany	Europe
Grothmann and Reusswig, 2006	2006	Surveys	Germany	Europe
Keller et al., 2006	2006	Experiments	Switzerland	Europe
Karanci et al., 2005	2005	Experiments	Turkey	Europe
Schirillo and Stone, 2005	2005	Experiments	USA	North America
Baan and Klijn, 2004	2004	Literature review	Netherlands	Europe
Mileti et al., 2004	2004	Literature review	N/A	Global
Parker, 2004	2004	Literature review	N/A	Global
Pornpitakpan, 2004	2004	Literature review	N/A	Global
Rohrmann, 2004	2004	Content analysis	N/A	Asia
Zhang et al., 2004	2004	Surveys	USA	North America
Lindell and Perry, 2003	2003	Content review	N/A	Global
López-Vázquez and Marván, 2003	2003	Interviews	Mexico	North America
White and Howe, 2002	2002	Content review	UK	Europe
Mileti and Peek, 2000	2000	Literature review	N/A	Global
Lipkus and Hollands, 1999	1999	Content review	N/A	Global
Covello et al., 1986	1986	Literature review	N/A	Global

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