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The European Flood Awareness System and its integration with national flood warning systems

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Abbreviations

BPM	Business Process Modelling
BPMN	Business Process Modelling Notation
CPA	Civil Protection Agency
DSR	Design Science Research
EFAS	European Flood Awareness System
EPC	Event-driven Process Chain
EPS	Ensemble Prediction System
ERCC	European Response Coordination Centre
EWS	Early Warning System
FEWS	Flood Early Warning System
FRG	Flood Risk Governance
FRM	Flood Risk Management
FRMP	Flood Risk Management Plan
GoM	Grundsätze ordnungsmäßiger Modellierung
SOV	Single Official Voice
STAR-FLOOD	STrengthening And Redesigning European FLOOD risk practices Towards appropriate and resilient FRG arrangements
UN-ISDR	United Nations International Strategy for Disaster Reduction

1 The European Flood Awareness System and its integration with national flood warning systems

Following devastating floods and associated responses on a global, European and national level Flood Risk Management (FRM) has undergone a number of shifts in recent decades. On the international level, these are embodied by the United Nations 2005 Hyogo Framework for Action and the United Nations 2015 Sendai Framework for Disaster Risk Reduction. On the European level, the European Union 2000 Water Framework Directive and the European Union's 2007 Floods Directive have shaped the direction of national level reform. These shifts include moving from "flood defence to Flood Risk Management" (Butler & Pidgeon 2011), away from only "keeping water from people" via structural measures toward diversifying and combining different approaches (Dieperink et al. 2016, p. 4468) , from reactive to proactive handling of floods (Mehryar & Surminski 2021), toward more involvement of local level actors and coordination of various government agencies involved in water management, spatial planning and FRM (Wiering et al. 2017). Between the systems in which these reforms were to be carried out considerable variance has been observed in the literature, as existing Flood Risk Governance (FRG) arrangements differ in what measures they focus on (Hegger et al. 2014), how risk is institutionalized (Krieger, 2013; Rothstein et al. 2011) and how flood risk is understood and assessed (Albano et al., 2015). This reform drive also included the proliferation of increasingly sophisticated early warning systems to enable preparatory actions and response planning. In 2019, the number of Flood Early Warning Systems (FEWS) operated had doubled compared to 2000 (Perera et al. 2020, p. 1). The European Union Floods directive (2007, p. 31) practically required member states to develop flood early warning capabilities.

Early Warning Systems can only provide value, if the lead time provided by a warning is capitalized on to appropriately prepare for a flood to protect lives and assets. Flood early warning is, however, notoriously difficult, as issues can occur in any part of the early warning system and then propagate to following parts of the system (Parker & Priest 2012, p. 2929). FEWS frequently failed due to numerous barriers to successfully capitalize on warnings (Parker & Priest 2012; Perera et al. 2020; Sukhwani et al. 2019).

This paper proposes a reference model for the integration of flood warning information from a Europe-wide monitoring system, the European Flood Awareness System (EFAS), into decision-making processes by national flood warning and civil protection authorities. The reference model was developed following Peffers et als. (2007) Design Science Research (DSR) Methodology. This methodology includes six steps forming a cycle that can be iterated several times. For this article, two iterations of the cycle were performed.

1.1 Motivation and Relevance

The following section introduces and motivates the problem this paper aims to address and ends by stating the research goal. The problem this paper aims to address are barriers to utilizing EFAS information for decision-making in national warning systems. EFAS partners operate in a variety of institutional contexts. How EFAS information is used should thus be situated within the wider frame of national FRG and the role of early warning within different national arrangements.

Under the 2007 Flood's Directive, EU member states conducted flood risk assessments and created Flood Risk Management Plans (FRMPs) for each river basin. Countries were practically required to set up a FEWS and the European Union highlighted EFAS as complementary information to be used to improve national early warning systems (European Commission 2021 p. 16). EFAS information provides an overview of potential flooding across Europe, given its cross-border nature (Smith et al. 2016 p. 315). EFAS provides medium-range flood forecasts and notifications to national meteorological authorities, a capability that was often less well developed nationally. EFAS is an Ensemble Prediction System (EPS), meaning that it accounts for uncertainties in modelling initial states and development of hydrological systems to provide an ensemble of forecasts, displaying a range of potential outcomes. In this way, EPS forecasts provide a probabilistic forecast, that can be useful for identifying likely and worst cases to plan for (Demeritt & Nobert 2011 p. 128). At the time, EPS forecasts promised longer lead times and more accurate probabilities than deterministic flood forecasts often used primarily at national forecasting agencies (Demeritt & Nobert 2011 p. 129). EFAS was set up as to not interfere with the "one-voice warning mandate" (Smith et al. 2016 p. 315), also called "Single Official Voice principle" (Silingardi 2019, p. 1) stipulated by the World Meteorological Organization. According to this principle, national meteorological services should be the single authoritative source of warnings within a country (Silingardi 2019). Throughout the thesis the term "Single Official Voice principle" (SOV) is used. The European Commission (2021, p. 16) highlights EFAS as complementary information to improve FRM on the national level. Because of the SOV principle, EFAS' mandate ends once information has been provided to national partners. There have been no studies of how EFAS is used by different partners within national FEWS since the system has become operational to the author's knowledge.

Dissemination and communication of alerts was frequently identified as one of the more vulnerable parts of FEWS (Basher et al. 2006, p. 2168; Perera et al. 2020, p. 2). Coordination and communication problems between various government agencies were often cited as one of the main problems relating to dissemination and communication issues (Basher et al. 2006, p. 2172-2174; Silingardi 2019, p. 170; Sukhwani et al. 2019, p. 12). More recently, similar problems seem to have plagued disaster responses in Belgium and Germany during the 2021 summer floods, were authorities appeared hesitant to act on EFAS alerts they had received (POLITICO 2021). This hesitancy to act on EFAS alerts has been observed in the literature, when the system was at a very early stage (Demeritt et al. 2013, p. 153-155). It was connected to institutional contexts making it difficult to act on probabilistic information and a focus on short-term warning against high certainty, with emergency plans being activated on shorter time scales than EFAS lead times (Demeritt 2013, p. 153-155).

Following the World Bank Group's (2019) Design for Impact Framework, this article focusses on impactful use of EFAS information, where "impactful use is … the effective development and communication of data or information in ways that result in decision-making that reduce the consequences of disaster risk" (World Bank Group 2019, p. 18). The hesitancy of national authorities to act on EFAS information suggests that there are sometimes barriers to their impactful use. Scholars also highlighted the need to pay more attention to the institutional learning capabilities of FRG arrangements (Sawalha 2020, p. 474f; Thieken et al. 2016, p. 9). Post-flood lesson-drawing exercises were often not structured and did not lead to recommendations (Thieken et al. 2016, p.9). EFAS continues to add new partners, and existing partners may re-evaluate their use as the tool is further improved. The reference model can aid re-evaluation by depicting current EFAS usage and highlighting alternatives.

1.2 Research Goal

This paper aims to propose a reference model for communicating EFAS information in national early warning systems to overcome barriers to their use for decision-making. The main stakeholders for this reference model are then EFAS and the users of EFAS information. The reference model is considered a success if it is understood and considered useful by these stakeholder groups. The model focusses on how EFAS information is communicated and feeds into different functions and products in national flood warning systems.

2 Methodology

In the following section, the methodology used in this article is outlined. First, the Design Science Research Cycle is explained. Then it is outlined how each step in the cycle will be conducted for this article.

2.1 Design Science Research Cycle

This paper adopts a Design Science Research methodology with six steps forming a cycle that can be iterated several times following Peffers et al. (2007). In the first step, a problem is identified and motivated. Next, objectives for a solution are defined based on the problem knowledge. The artifact is designed, utilizing literature knowledge. The last three steps are to demonstrate the artifact fulfills its purpose, evaluate it in a suitable context and then communicate the results. Evaluation is crucial to demonstrate that an artifact provides a solution to the identified problem (Peffers et al. 2007, p. 56) and makes a research contribution (Hevner et al. 2004, p. 85-87).

To ensure rigorous model design, two iterations of the Design Science Research cycle were performed for this paper. The output of each cycle was evaluated through interviews and adapted to the outcomes of the evaluation. In the first cycle, the problem was identified and motivated, problem specifications were developed based on a structured literature review and Design Objectives for a solution were derived. In the second cycle, the reference process model was designed and evaluated.

The problem identification and motivation activity ensures that the problem is defined, and the value of a solution justified (Peffers et al. 2007, p. 52). The problem identified in this article was introduced in the motivation as barriers to utilizing EFAS information for decision-making in national FEWS. The value of the solution is to aid in evaluating EFAS use, identify and overcome barriers and as a result utilizing EFAS information more effectively. As a result, improvements in the national FEWS, like improving forecasters confidence in their predictions, aiding decision-makers or saving time for focusing on other activities could be realized. Peffers et al. (2007, p. 52f) note that it can be useful to atomize a problem to ensure the solution matches the aspects of the problem. For this reason, problem specifications were created based on a structured literature review following Webster & Watson (2002). EFAS information flows through different national EWS alongside other information it is processed with. It is also accessible to actors at different points within those systems, including forecasting agencies but also in some cases civil protection authorities. Problems can occur at any point in FEWS and are then passed along (Parker & Priest 2012, p. 2929). Barriers to utilizing EFAS information but also early warning information more generally are also linked to the wider institutional context (Demeritt et al. 2013, pp. 154–156). Therefore, the structured literature review focused on identifying barriers to flood early warning across the broader context of FRG.

Following that, Design Objectives were developed based on the problem specification, making sure each aspect of the problem specifications was covered. They were then evaluated through an initial interview series with academic experts and practitioners. Design Objectives were then sharpened by updating them based on the evaluation outcome. In the second cycle, a prototype of the reference model was developed, and a prototype evaluated through a second series of interviews. The model was then adapted to reflect the outcome of the evaluation interviews. The final model was sent to interviewees along with a textual description for final comments and approved by the interviewees.

In the following sections, first the reference model concept adopted in this article is introduced and the approach used to design and adapt the reference process model is explained. Then, the interview methodology for conducting the evaluation interviews is outlined.

2.1.1 Evaluation Methodology – Semi-structured interviewing

Two series of evaluation interviews were conducted for this thesis. The first series of five interviews aimed at evaluating Design Objectives as well as gathering a knowledge base for designing a reference process model. It was expanded by an additional four interviews to broaden the knowledge base for constructing the model. A second series of four follow-up interviews and two additional interviews was conducted to evaluate the resulting reference model and gather information for discussing the model.

Interviews allow constructing knowledge between the researcher and key informants (Recker 2012, p. 117). Key informants in this case are the reference model's stakeholders and thus flood forecasters, flood forecast users and academic researchers on flood warning. Interviews can be structured, semi-structured or unstructured (Bryman 2012, p. 469f; Recker 2012, p. 118f). In structured interviews all questions are pre-planned. Structured interviews have the advantage of increased comparability, at the expense of flexibility to explore topics of interest emerging during the interview. Unstructured interviews are conducted with very little pre-planned inputs and allow interviewees to describe topics from their point of view, emphasizing what they view as important. Semi-structured interviews retain flexibility while providing a frame to make interviews more comparable in the form of an interview guide (Bryman 2012, pp. 471–474). An interview guide can be a basis for discussion, as well as a list of starting questions (Bryman 2012, p. 471).

The advantage of semi-structured interviews is that they allow to focus on understanding the interviewees point of view on their work and what they view as relevant. Semi-structured interviews can be more or less structured to allow for the right amount of flexibility to adjust questions to what the interviewee is saying. Semi-structured interviews allow interviewees to voice needs, viewpoints, and concerns without presupposing them, while remaining comparable (Bryman 2012, pp. 469–474; Recker 2012, p. 118f). Thus, in summary, semi-structured interviews with stakeholder groups are an appropriate tool for evaluating requirements for a reference model.

Myers & Newman (2007, p. 10) found that while semi-structured interviewing has been used widely in Information Systems research, reporting about aspects of the interview process was frequently lacking. Therefore, the following paragraphs outline the interview process across the two interview-series conducted for this paper.

A total of 15 interview were conducted. The first five were conducted between the 11^{th} and the 19^{th} of March 2022, an additional four were conducted from the 20^{th} to the 26^{th} of March. The second series of four interviews was conducted between May the 5^{th} and May 10^{th}, with two additional interviews on June 2^{nd} and June 7^{th}. Interviews were conducted using Zoom, except for two interviews which were conducted via Microsoft Teams. 14 interviews were conducted in English and 1 interview in German. Interviewees were contacted via email. For the initial four interviews of the first series, a visualization of the Design Objectives and, upon request, a list of starting questions was sent, acting as the interview guide. For subsequent interviews, the visualization of Design Objectives was dropped, but starting questions were generally sent. For the second series of interviews, only an invitation for a follow-up interview was sent. The interview guide, in this case, was the presentation of the reference model and starting questions on its clarity and accuracy. For the final evaluation, the model was sent to interviewees, including the textual description in chapter 4.6. For the additional two interviews, the model was sent beforehand and also presented during the interview.

Interviews were recorded and afterwards transcribed. Transcripts were then also sent to the interviewees. Interviews are anonymized in this thesis. Interviewees are thus referred to in general terms by their roles. These roles were national forecasters, emergency managers, as well as two people in management roles. An overview of the interviews is included in Annex **Fehler! Verweisquelle konnte nicht gefunden werden.**.

The initial five interviews involved two interviews with academic experts, one interviewee at national forecasting agencies and two interviewees at EFAS centres. The four additional interviews involved one interviewee at a civil protection authority on a local level, one interviewee at a civil protection authority on a regional level, one interviewee at an EFAS centre and one interviewee at a national forecasting agency. Some of the EFAS centres also functioned as national forecasting agencies. The four follow-up evaluation interviews involved two interviews at national forecasting agencies, one interview with an academic practitioner and one interviewee at an EFAS centre. One of the interviews involved two interviewees, a flood forecaster and a manager. The additional interviews involved a national civil protection authority and a regional forecasting agency to broaden the evaluation's perspective.

Eleven of the practitioner interviewees worked at EFAS full partner institutions and two interviewees at institutions that were third party partners, namely a national civil protection authority and a local authority.

In the interviews, interviewees were asked about the national FEWS and the use of EFAS therein from the forecasting agency up to the activation of response actions. The interviews with national flood forecasters and emergency management agencies included organizations across seven countries with one country from which two organizations, a forecasting and a civil protection organization were included in the interview-series. Interviewees were able to outline the organizations involved across the whole process from EFAS dissemination to activating response, but how much they were involved in and able to describe processes by these other organizations varied. National forecasting agencies sometimes had a limited view on the activities of civil protection authorities receiving their warnings and vice versa. In other cases, forecasting agencies and civil protection authorities had more insight into the activities of the other organization and there was more direct involvement. To address this partly, the interviews with academic experts were conducted to get input and later feedback, from a more holistic point of view. It remains a limitation of the paper. The activities of national flood forecasters described in the model are then based on 11 of the interviews and the activities of emergency managers are based on 8 of the interviews.

The following section outlines the first iteration of interviews conducted for this study, including the approach followed.

2.1.2 Reference Modelling

Reference models are information models that are meant to be reused to improve the efficiency and effectiveness of creating new information models (Vom Brocke 2007, p. 49; vom Brocke & Buddendick 2004, p. 19f). New models created using a reference model are called application models. For this study, a reference model was constructed. There are different design principles for both constructing and applying reference models (Vom Brocke 2007; Vom Brocke & Buddendick 2004). These are called configuration, instantiation, aggregation, specialization and analogy. Configuration means constructing different versions of a reference model that can be selected depending on the type of application. Instantiation means the reference model consists only of generally valid contents and spaces for adaptation are marked by placeholders. Aggregation means that a model is constructed by aggregating contents from several other models. Specialization means creating a specialized model with changes from a general model. Analogy means applying similar solutions to a new problem in a creative way. The reference model in this study is intended to be reusable, to create information models for national flood warning systems to start using or to improve current use of EFAS information.

Currently there is no general model concept in the literature on reference modelling. Rather, different approaches exist. To choose an appropriate method of evaluation for a reference model, the underlying assumptions and the approach this study adopts to reference modelling are outlined in the next paragraph following Becker et al. (2004).

This study adopts an approach to reference modelling based on moderate constructivism. From this perspective, knowledge is acquired by constructing reality through a language owned by a language community (Becker et al. 2004, p. 3-9). A consensus approach to truth is adopted, according to which a model statement is true, if members of the language community agree that it is. The language community for this article are national recipients of EFAS information, the EFAS centers as well as academic researchers. Thus, interviews with members of this language community are appropriate for evaluating and informing Design Objectives and specifications, as well as model prototype and final instance.

The following paragraph outlines how the model was designed using reference model construction techniques. The information base for designing the model were the five Design Objective evaluation interviews as well as the four further interviews. During these interviews, interviewees described their organization’s processes, like how flood forecasts were created and disseminated or how responses are initiated, and how they use EFAS information. First, different uses for EFAS were distinguished. Descriptions of these uses were marked in the transcripts and process model fragments were designed based on them. These process fragments were then compared, and a general process was designed based on similar functions found across interview transcripts. For each function in the general model where differences existed across interviews, an instantiation was designed. The different uses were designed as separate processes and summarized into one model by aggregation.

For creating the reference model, the article follows the Guidelines of Modelling (GOM II) as described in Schuette & Rotthowe (1998, p. 245-249). These are the principles of construction adequacy, language adequacy, clarity, systematic design, comparability and economic efficiency. Construction adequacy requires a consensus about the model and the problem. This was achieved by evaluating Design Objectives and designing and evaluating the model based on stakeholder interviews. Language adequacy requires the correct use of an appropriate modelling language. For lack of a domain-specific modelling language and no usage of process modelling among interviewed stakeholders, the Event-driven Process Chain (EPC) was used, as an easy-to-understand and flexible modelling language. To ensure clarity, systemic design and comparability, the model was designed after building a reference model frame and using aggregation and instantiation for constructing the model. The principle of economic efficiency is difficult to apply. In the reference model, different uses of EFAS and variations were depicted by functions performed within these uses. Different variations for how partners perform these functions were modelled by instantiation and the different uses structured by aggregation. This abstracts some complexity in terms of organizational level and specific characteristics away and depicts uses of EFAS information at an appropriate level of abstraction to situate and evaluate them. However, abstracting these characteristics away also raises costs of applying the model, as they need to be added by specialization or further instantiation, where relevant.

3 Design Science Cycle Iteration 1: Creating Design Objectives

During the first design science cycle, the Design Objectives for the reference model were created. They were derived from problem specifications, synthesized from a structured literature review. The Design Objectives were then evaluated and adapted through a series of interviews. First, the results of the literature review are presented. Following that, the problem specifications are introduced, and the preliminary Design Objectives outlined. Finally, the evaluation of the preliminary Design Objectives and subsequent changes are outlined, concluding the first Design Science Cycle.

3.1 Structured Literature Review

To thoroughly create the problem specifications and derive Design Objectives, a structured literature review following Webster & Watson (2002) was conducted for this article. There is limited literature focussing specifically on the communication and use of EFAS alerts. In addition, the use of EFAS in different early warning systems needs to be viewed in connection with the wider FRG context. Therefore, the literature review focussed on identifying barriers to early warning stemming from the institutional context found in the literature.

Cooper (1988) presents a taxonomy of literature reviews comprising 6 characteristics: 1) focus, 2) goal, 3) perspective, 4) coverage, 5) organization and 6) audience. The taxonomy is useful to evaluate the quality of a literature review in fulfilling its purpose.

In the following, the taxonomy is applied to outline the goals of the literature review on FEWS. The literature review conducted for this study 1) focussed on identifying theories and research outcomes to 2) conceptualized central issues relating to institutional barriers to flood early warning. The review 3) took a neutral position and 4) covered a representative subset of the relevant literature. It was 5) organized by grouping papers according to different concepts used therein and 6) aimed to identify findings relevant for scholars as well as policy makers. The literature was considered to adequately fulfil these characteristics.

Webster & Watson's (2002) approach was appropriate to fulfil these goals as it is a concept-centric method that can be used to collect and organize a representative sample of the relevant literature.

Papers were gathered from Web of Science and Scopus across three queries. The review was conducted in February 2022. The queries were added successively, to cover relevant literature, when it emerged that the original query didn't cover the problem comprehensively. Searches were limited to include only articles with the query keywords included in their abstract, titles or keywords, to make sure they actually focussed on the search term. Web of Science was chosen for the review because it offers a convenient functionality for backwards forwards searching. Scopus was used in addition, to ensure a rigorous search.

The first query was: “European Flood Awareness System” OR “European Flood Alert System”. It returned 41 results on Web of Science and 39 results on Scopus. There is little literature directly addressing EFAS, and technical aspects tend of the system tend to be more in focus, with some exceptions. Therefore, two additional searches were conducted, to include broader literature on flood early warnings as well as the broader configuration of institutions working to anticipate, mitigate or prevent flood risk. The second query was: “Flood early warning” and returned 222 results on Web of Science and 306 results on Scopus. The third query was: “Flood Risk Management” AND “Governance” and returned 393 results on Web of Science and 288 results on Scopus.

Papers were selected through several rounds of first skimming titles and abstract and then reading the papers still left in the second round, removing further papers. During the first round, concepts were identified and used to group and select papers. Papers were kept, if they explicitly addressed concepts that were deemed relevant to situate and understand the topic of the review, institutional barriers to flood early warning. Concepts are presented from broadly to more narrowly covering the organizational aspects of FEWS. Selected papers were scanned backwards and forwards for additional relevant literature. The inclusion of new papers was stopped when no new relevant concepts appeared as suggested by Webster & Watson (2002, p. 16)

A final total of 45 papers were included for review. In total, 7 concepts to group the literature were identified that will be discussed in the literature review. Papers were only counted as including a concept, if it was not only mentioned, but also explained or applied in greater depth. For instance, most papers mentioned the word resilience, but less elaborated on the concept. A concept matrix listing papers and concepts can be found in Annex **Fehler! Verweisquelle konnte nicht gefunden werden.**.

In the following section, each concept is explained and related issues relevant for early warning found in the literature are explained in-depth.

3.1.1 Concepts

First, the concepts are outlined and set in relation with one another.

The wider institutional context within which Flood early warning is placed, is captured by the concept Flood Risk Governance (FRG). FRG refers to constellations of a wide range of actors engaged in managing flood risk (Hegger et al. 2014, p. 4131). The concept is used to analyse how flood risk is approached and changes over time across countries. In highlighting differences in approach and dynamics, different strategies to managing flood risk are identified in the literature.

A conceptualization of risk was included in most papers, as an understanding of risk often forms the basis of reasoning about aspects of dealing with flooding, like different strategies or goals. Risk is also discussed in more general terms and applied to scenarios other than flooding. For FRM, the literature applies risk to differentiate approaches to flooding (Dieperink et al. 2016), examines the use of risk-based policy (Krieger 2013), flood risk mapping (Albano et al. 2015), risk communication by governments (Demeritt & Nobert, 2014) and discusses risk-based approaches to decision-making (Dale et al. 2014).

Resilience broadly describes how well a system exposed to flooding can avoid negative outcomes (Hegger et al. 2016, p. 2f). Different definitions of the concept exist, that correspond to viewpoints on what is needed to avoid or overcome negative outcomes of flooding.

Measures in FRG can be grouped into various FRM strategies. In the literature these are categorized by underlying understandings of flood risk or resilience (Hegger et al. 2016; Matczak et al. 2015). The most-used conceptualization of different FRM strategies is the flood risk cycle (Matczak et al. 2015, p. 196), also called safety-chain (Ten Brinke et al. 2008). Here, measures are grouped around different stages of flooding in a cycle. This concept is used both in the literature and policy, to identify whether FRG sufficiently addresses all stages of floods and whether there are gaps or weaknesses.

Preparation or Preparedness is the term used for the stage of the Flood Risk Cycle where FEWS are situated (Dieperink et al. 2016; Ten Brinke et al. 2008). Preparations refers to FRM strategies aimed at proactively taking steps to reduce the consequences of a flood. Next to FEWS, the preparation stage also includes contingency planning. The concept is used to evaluate the capabilities for preparatory actions of FRG arrangements or understand shifts in those arrangements.

Flood Early Warning is an important aspect of preparedness (Mysiak et al. 2013, p. 2886). Literature on early warning defines components of warning systems, their links (Basher et al. 2006) and identifies challenges and limitations of early warning (Perera et al. 2020). Early warning systems are not only examined with relation to flooding but are often approached from a more abstract perspective that can include not only natural disasters but a wide range of scenarios, including for example armed conflict (Choo 2009). The overarching challenge, this paper focusses on are organizational factors influencing the effective use of warning information to enable responses reducing the consequences of an impending flood. The literature examines responses by government, as well as different societal groups or the general public (Perera et al. 2019). This article deals with the use of warning information as a decision-input for government actors. Literature approaching early warning from a broad angle was included if it addressed organizational use of warning information.

Within this broader literature, there are also challenges that apply more specifically to flood early warnings and EFAS information. The communication and use of probabilistic information, like EFAS ensemble forecasts, presents a particular challenge that is analysed in the literature (Morss 2010; Nobert et al. 2010). Any forecast has uncertainty associated with it, however, this is not always communicated or incorporated in decision-procedures. Literature makes recommendations for appropriate communication and decision-making techniques and identified preconditions and barriers for using probabilistic information (Arnal et al. 2020; Höllermann & Evers 2017; Nobert et al. 2010).

The following sections introduces the literature grouped with each concept.

3.1.2 Flood Risk Governance

Hegger et al. (2014, p. 4128f) define FRG arrangements as institutional constellations of actors, their discourses, rules, power and resource base. Through these FRG arrangements various FRM Strategies are realized. How these strategies are realized also depends on dynamics in responsible organizations. Implementing new strategies may also lead to changes in the governance arrangement (Hegger et al. 2014, p. 4131). The organizations involved in FRG can include organizations responsible for spatial planning, disaster management or water management (Hegger et al. 2014, p. 4131).

FRM Strategies are approaches to reduce the probability of flooding, its consequences or bolster recovery from flooding. FRM strategies have in common that they aim to improve resilience to flooding, however they focus on different aspects of resilience (Driessen et al. 2018, p. 2-5). Different outcomes and approaches between countries partly rest on different understandings and operationalization of flood risk and different views on resilience.

The following section discusses different dynamics that have shaped changes in national FRG arrangements in recent decades. These dynamics have been examined in the literature in the context of moves to diversify national FRM Strategies to better cover different aspects of flood events. Much of the literature discussing this found during the review was based on or referred to the "STrengthening And Redesigning European FLOOD risk practices Towards appropriate and resilient FRG arrangements" (STAR-FLOOD) Project, which ended in 2016 (https://cordis.europa.eu/project/id/308364/reporting).

Both academic literature and policy-documents at different scales, including the EU Floods Directive and the Hyogo Framework, favoured utilizing multiple FRM instruments to effectively address each aspect of flood risk (Dieperink et al. 2016, p. 4468). The argument went, that a lot of countries relied heavily on structural defences, that were no longer able to sufficiently prevent negative outcomes to flooding, due to increased urbanization and climate change (Driessen et al. 2018, p. 12; Hegger et al. 2016, p. 9). This reliance was then argued to create a cycle of increased pressures to maintain structural defences which keep attracting development to at-risk areas (Butler & Pidgeon 2011, p. 540). This in turn was argued to worsen vulnerabilities to failures of flood defences (Hegger et al. 2016, p. 9). As building a completely "fail-safe" system was deemed infeasible (Hegger et al. 2016, p. 9), the literature called for building a system that can "fail safely" (Dieperink et al. 2016, p. 4468).

The implementation of FRM Strategies can be realized through different instruments but was found to predominantly rely on legislative means. Gralepois (2019, p. 71-77), built on the STAR-FLOOD analysis, comparing not only the emphasis on different FRM strategies, but also what instruments were used to achieve them in England, France, and the Netherlands. Distinguishing legal, economic, incentive-based, standards or information instruments, they find that legal instruments were the dominant instrument used. Standards were barely used at all. Interestingly, they find that the majority of instruments addressed prevention, but also preparation. Specifically for the preparation strategy, all three countries used legal and information-based instruments, and England used all instruments but standards (Gralepois 2019, pp. 77–87).

By diversifying the portfolio of FRM strategies the various aspects of resilience (Hegger et al. 2016), and the different stages of the FRM Cycle (Schelfaut et al. 2011, p. 826) can be covered. This involves moving from a reliance predominantly on flood defences, also called structural measures, to increasingly utilizing non-structural measures as well, including early warnings (Krieger 2013, p. 237). The literature described strong path-dependencies associated with structural flood defences (Matczak et al. 2018, p. 246;

Wiering et al. 2018, p. 52). Conflicts could arise from newly envisioned FRM goals clashing with those of cities protected by dikes, wishing to attract development (Butler & Pidgeon 2011, pp. 540–542). The literature cited significant challenges of diversifying an existing FRM Governance arrangement of coordinating different actors, aligning employed strategies (Dieperink et al. 2016, p. 4475-4477), or addressing path dependencies and trade-offs (Matczak et al. 2018, p. 246). If these path dependencies remained unaddressed, attempts to diversify, and change an existing arrangement may end up mainly reinforcing the existing arrangement (Matczak et al. 2018).

The development and implementation of EFAS also did not occur in isolation, but as part of a bigger push for reform in European FRM following severe floods in the 90s and early 2000s (Demeritt & Nobert 2011, p. 134f). Development of EFAS started in 2003 and finished in 2013 (Smith et al. 2016, p. 314). The system's development coincided with the implementation of the 2007 Flood's Directive and making use of EFAS has been recommended in subsequent implementation reports on the directive. Given that how the directive is implemented is largely at Member States' discretion, outcomes vary based on existing FRM arrangements and dynamics (Hegger et al. 2016; Wiering et al. 2017). EFAS was no exception to this. Demeritt et al. (2013, p. 153-156) noted wider institutional obstacles to making use of EFAS alerts in some countries. Already in its creation, EFAS was shaped by turf wars and concerns over mission creep and accountability issues by member states (Demeritt & Nobert 2011, p. 134-137). As a result, EFAS was developed to supplement national capacities, by providing medium-range probabilistic forecasts, a capacity often less well developed on the national level. In addition, EFAS information is only publicly available through national agencies, to avoid conflicting sources of information and stay in line with the one voice warning mandate (Smith et al. 2016, p. 315). While EFAS was still in its testing phase, it was possible to leave questions around responsibilities connected to the system unanswered for partners (Demeritt 2011, p. 136). Now that the system is operational, deferring these questions may no longer be a possibility. Barriers to acting on EFAS alerts thus need to be understood in the wider context of shifts in FRG.

3.1.3 Risk

One of the ways in which national systems differ, is how Flood Risk is understood. Flood Risk is mainly defined in two ways (Albano et al. 2015, p. 2706). The first definition views flood risk as the probability of a flood times its consequences. The second definition considers flood risk as hazard (including probability of occurrence) times exposure (people and assets that would be affected) times vulnerability (how vulnerable the exposed populations and assets are to flooding). The models used for flood risk assessment at different scales varied widely across Europe in terms of what characteristics are considered and the resulting model outcomes (Albano et al. 2015, p. 2714-2716).

Those risk assessments and flood hazard maps formed the key basis for planning decisions under the EU 2007 floods directive. The directive thereby moved FRM in the EU moves toward risk-based governance (Krieger 2013, p. 237). Risk-based governance means quantifying risks and allocating scarce resources based on it. Krieger (2013, p. 239), adopted a definition of risk-based governance comprising of three elements: Science-based quantification, expressing consequences as monetary value and assessing probabilities to clarify uncertainty as far as possible. Risk-based governance is theorized to be driven by pressures for increased efficiency and accountability, as it can both help better allocate resources as well as to better justify choice made (Krieger 2013, p. 239f). An example for such accountability pressures in FRM is an Italian court's interpretation of uncertainty and predictability of floods as described by Mysiak et al. (2013, p. 2887): If an event can occur and an average time for its reoccurrence can be estimated, it is not exceptional or unforeseeable and authorities can be held accountable for not reacting appropriately to it.

Managing floods has seen a similar shift starting in the 90s, described as moving from "flood defence to FRM" (Krieger 2013, p. 237). This shift entailed moving away from a predominance of large-scale structural flood defences (structural measures) increasingly failing to fulfil their purpose and using a wider range of approaches including many non-structural measures, like early warnings.

The 2007 Floods Directive, which included mandatory flood risk assessments that needed to be made publicly accessible and promoted non-structural measures, is no exception in this. Krieger, (2013) demonstrated that the spread of risk-based approaches came with considerable variance comparing FRM in England and Germany. The seeming adoption of risk-based policies across Europe did not reflect convergence due to different conceptualizations of risk.

Additionally, Krieger (2013, p. 242-244) showed how risk-based approaches faced considerable barriers depending on institutional and legal contexts. In Germany, the legacy of focussing on structural defences was that legal definitions focussed on protection standards of structural defences, in this case protection against floods with a return period of 100 years. Development was banned on land with lower return periods. In England, vulnerability was taken into account, to treat for instance, commercial and residential areas differentially. Risk assessment in Germany incorporated the effects of flood defences. This was because these assessments justify interventions into property rights and revealing uncertainty opened decisions based on them up to legal challenges.

In England, displaying uncertainties had an opposite effect, where indicating a risk to a property protected by structural defences allowed deflecting blame for damages to that property. As a result, protective effects were discounted when displaying the extent of potential flooding (Krieger 2013, p. 242f). The way risk assessments were incorporated by laws and procedures further interacted with subsequent FRM measures in ways that may not always have been intended.

Underlying risk-based governance are modes of risk communication, referring to how risk information is passed back and forth between experts, practitioners and the public (Demeritt & Nobert 2014, p. 1). Demeritt & Nobert (2014) outlined four models of flood risk communication, based on whether communication is one-way or two-way and whether it occurs for normative or instrumental reasons. Flood warnings are generally viewed as valuable only if decisions are taken based on them to reduce consequences of flooding (see cf: Parker & Priest 2012; UNISDR 2006). This implies an instrumental mode of risk communication, where risk information should influence behaviour of government and the public. The risk communication model most in line with this perspective is the risk instrument model. This model draws on social psychology to examine the purpose of risk communication and its effect on behaviour of recipients to make recommendations, for instance about how to design flood risk information for different audiences (Demeritt & Nobert 2014, p. 5-7). Another model of risk communication is the risk government model. This perspective is frequently used to explain the effect of risk communication on governance, focussing on how risk communication shapes exercises of power and responsibility distribution (Demeritt & Nobert 2014, p. 9-11). In practice Demeritt & Nobert (2014, p. 12), concluded that rationales of risk communication were not always matched to purposes which can lead to contradictory recommendations.

Literature dealing with barriers to early warning also discussed risk-based views on communicating and making decisions based on warnings. Choo (2009, p. 1074-1078) proposed examining the use of cost-benefit analysis to set an optimal decision-threshold that balances the risk of false and correct alarms (hits). As an alternative to cost-benefit analysis for setting decision-thresholds, Choo (2009, p. 1079) discussed a precautionary approach which would entail issuing warnings against low thresholds and accepting a higher rate of false alarms. False alarms, however, carry their own costs, which are discussed in the section on early warning concepts. Höllermann & Evers (2017) conducted a study on how practitioners handle scientific uncertainty information. Interviewing water management professionals in Germany, they found that they implicitly used risk thinking to approach uncertainty. Höllermann & Evers (2017, p. 16f) recommended incorporating explicit risk-based decision-making approaches to translate uncertainty for practice. Dale et al. (2014) developed a risk-based decision approach to act on probabilistic flood forecasts for forecasters and warning decision-makers for the UK government. Aside from acting as a translation of scientific information, they highlighted this would enable taking decisions earlier, make decisions more traceable and enable cost-benefit based precautionary responses but also cost savings (Dale et al. 2014, p. 12f). Arnal et al. (2020, p. 217), proposed for the UK's Flood Forecasting centre to co-develop a risk-based decision-making approach with Environmental Agency Duty Officers, the UK's warning decision-makers.

Risk-based approaches to flood management have been criticized for potentially becoming mere blame-shifting exercises (Butler & Pidgeon 2011, p. 545). This can occur if reforms focus more on redistributing responsibilities than providing the tools to fulfil them or resolving constraining conflicts (Butler & Pidgeon 2011, p. 541). Barriers thus need to be explicated and addressed when proposing risk-based approaches. In addition, answering questions of responsibility and accountability needs to be accompanied by examining "processes of delivery" (Butler & Pidgeon 2011, p. 546). To communicate flood risk information to impact decision-making, attention thus needs to be paid both to the distribution of responsibility as well as the purpose and usage of information.

3.1.4 Resilience

FRM literature and policies are frequently based on assessments of flood risk (Albano et al. 2015; Driessen et al. 2018, p. 2). The concept of resilience, on the other hand, is widely used in scientific literature to describe the goal and successful outcomes of FRM (Driessen et al. 2018, p. 2). The term originates from ecological research and has been used in a wide variety of fields (Hegger et al. 2016, p. 2f). In the context of natural hazards, resilience has been applied to social-ecological systems (Hegger et al. 2016, p. 2).

Resilience is also an important concept to understand shifting FRG in the last decades. Resilience has quickly gained popularity, due to the United Nations 2005 Hyogo Framework for action endorsing community resilience as a pillar of Disaster Risk Reduction (Schelfaut et al. 2011, p. 825). Here, it was defined by the United Nations Office for Disaster Risk Reduction (UN-ISDR) as a property that helps communities resist, absorb, accommodate, and recover from exposure to natural hazards (United Nations, 2005 p. 4).

Schelfaut et al. (2011, p. 825) highlighted that resilience has been defined in different ways, that are not entirely consistent. Hegger et al. (2016, p. 2) attributed this to the fact that resilience often accommodates both aspects of stability and change or adaptability simultaneously. For example, Sawalha's (2020, p. 476) concept of resilience includes an adaptive component where learning from past flooding is used to improve the system for the future.

Resilience is a multi-level concept that can be applied to all levels of government, but also society (Sawalha 2020, p. 476). Resilience is also achieved via a multitude of factors and tools. Schelfaut et al. (2011, p. 826) focussed on the role of flood policies and institutions, risk perception and communication and the use of flood management tools (from sandbags to warnings) by residents and authorities. Keating et al. (2017, p. 83-89), measured resilience across five dimensions as Financial, Human, Natural, Physical and Social Capital. Mysiak et al. (2013, p. 2886f), highlighted especially the knowledge aspect of resilience, as knowledge of “how to prepare, respond and recover” from flooding that can be deployed at different levels of a system, including individuals, as well as institutions. Mysiak et al. (2013, p. 2886f) used early warnings as an example of such deployable knowledge. Warnings can buy time, but this will only strengthen resilience if that time is used for preparatory or response measures. Schelfaut et al. (2011, p. 826) and Sukhwani et al. (2019, p. 2) cited effective early warning as a measure that is often more cost-efficient at bolstering resilience than structural defences or response and recovery.

Hegger et al. (2016) synthesized three perspectives on resilience that can be found in the literature as capacities of a community exposed to flooding. These are the capacities to resist, the capacity to absorb and recover and the capacity to transform and adapt. The capacity to resist draws on engineering resilience and describes measures aimed at negating the impact of flooding, like dikes (Hegger et al. 2016, p. 3). The capacity to absorb and recover draws on ecological and social ecological resilience concepts and describes how an area affected by flooding can “ absorb disturbances without shifting into a different, less satisfactory, state” (Hegger et al. 2016, p. 3). This refers to measures aimed at preparing for and recovering from flooding, including for instance early warnings. The capacity to transform and adapt draws on resilience concepts from the adaptive governance literature and refers to the capacity to adjust to external drivers of exposure to flood risk through institutional learning. Hegger et al. (2016, p. 10) also observed trade-offs, where a focus on flood defence/the capacity to resist seems to come with a lower capacity to absorb and recover.

Different understandings of resilience, reflect different understandings of desired outcomes to FRM efforts and thereby form the basis for various approaches to FRM. To achieve holistic FRM covering various aspects of resilience, diversifying the FRM strategies employed within FRG arrangements was recommended in articles based on STAR-FLOOD (see cf.: Dieperink et al. 2016; Driessen et al. 2018; Hegger et al. 2016).

3.1.5 Flood Risk Management Strategies

Specific strategies and measures to strengthen resilience to flooding can be grouped along a FRM cycle, although different definitions of it are in use. Generally, the FRM cycle consists of four phases: Mitigation/Prevention, Preparedness, Response and Recovery (Sawalha 2020, p. 471; Schelfaut et al. 2011, p. 826). Mitigation or Prevention describes measures taken before a flood strikes. Preparedness also takes place before a flood and can include early warning and emergency planning. Response relates to management of the flood while it is happening and Recovery to Relief efforts after the flood. Different versions of such a cycle are also used, for instance Kougkoulos et al. (2021, p. 1961f) described the French FRG arrangement as a cycle with the three components Risk Prevention, Emergency Management and Disaster Recovery, with warning included in the Emergency Management component. Mehryar & Surminski (2021, p. 142) distinguished pro-active FRM (risk assessment, risk reduction), preceding a flood and reactive FRM after a flood (response and recovery). In most countries, reactive FRM remained the main focus of legislation (Mehryar & Surminski 2021, p. 147). Other authors, addressing the adaptiveness aspect of resilience, modified the cycle to reflect arrangements for institutional learning (Sawalha 2020, pp. 474–477; Thieken et al. 2016, p. 9f).

This cyclical approach to flooding has also been adopted by policy-makers, like the US Federal Emergency Management agency, as well as EU countries, especially since the EU Floods Directive of 2007 is based on a FRM cycle, in this case the “safety-chain approach” (Ten Brinke et al. 2008, p. 93).

As part of the EU-funded STAR-FLOOD project, a distinction between five FRM strategies has been developed: Flood prevention, flood defence, flood mitigation, flood preparation and flood recovery (Driessen et al. 2018, pp. 3–5). In that order, the strategies can also be grouped along the FRG Cycle (Matczak et al. 2015, p. 196). The distinguishing factor lies in whether strategies aim at decreasing the probability of flooding, the consequences of flooding or prepare for recovery after a flood (Dieperink et al. 2016, p. 4469). Flood risk prevention focusses on decreasing the consequences of flooding, by reducing exposure of people, for instance by prohibiting settlement in flood-prone areas. Flood risk defence focusses on reducing the probability of flooding, for instance through dikes. Flood risk mitigation tries to reduce the consequences of flooding by redesigning the area at risk, for instance by flood proofing buildings. Flood preparation aims at reducing the consequences of flooding by preparing for it, for instance through warning and emergency planning. Flood recovery aim at bolstering the capacity to rebuild, for instance through insurance schemes.

Hegger et al. (2016, p. 3-7) related flood defence and flood risk mitigation to the capacity to resist and flood preparation, flood recovery, more natural forms of flood defence and flood prevention to the capacity to absorb and recover. Analysing six EU countries, the STARFLOOD project found flood defence to be dominant over the other approaches in four countries (France, Belgium, Poland and the Netherlands), while the other two (England and Sweden) had a more diversified approach, also strongly emphasizing Preparedness (Hegger et al. 2016). Hegger et al. (2016, p. 10) also observed trade-offs, where a focus on flood defence/the capacity to resist seemed to come with a lower capacity to absorb and recover. As examples of this, flood risk awareness and evacuation planning may be affected. Faith in structural flood defences can also lower risk awareness (Parker & Priest 2012, p. 2941). Evacuating large numbers of people living in flood prone areas protected by structural defences may not always be feasible (Ten Brinke et al. 2008, p. 96).

3.1.6 Preparation

Flood early warning is a key aspect of flood preparation strategies. As challenges to implement flood preparation, Dieperink et al. (2016, p. 4474) named risk awareness of involved actors, clearly attributing and linking responsibilities, and developing accurate warning systems and emergency plans. As actors and tasks involved, Dieperink et al. (2016, p. 4474) named forecasters, the agency disseminating the warning as well as emergency services that need to take action based on the warning.

Literature on early warning emphasized that benefits attributed to early warnings can only manifest through responses, like preparatory actions. The idea behind early warning, but also preparedness more broadly, is thus to anticipate potential future floods and act on the anticipation. An important distinction in this regard is between alert and vigilance procedures (Dedieu, 2010, p. 5f). A vigilance system is meant to bring issues to people’s attention, an alert system is meant to set off decisions.

Capabilities to respond to warnings can be organized by emergency plans. Alexander (2015) described early warnings and associated responses as a key element of emergency planning. Emergency plans are meant to appropriately match available resources to response needs, in a timely manner that avoids inefficient improvisation. The main way an emergency plan contributes to this goal is by ensuring effective communication and information management (Alexander 2015, p. 6-10). This involves clearly assigned roles, communication protocols and procedures for anticipated tasks. Warnings are described as a key element of emergency planning (Alexander 2015, p. 12f). An emergency plan needs to specify how warning information is transformed into advice on adequate responses, like sheltering or evacuating. Warnings have a technical, an organizational and a social component. The technical component consists of monitoring, the organizational component includes the decision to issue a warning and engage in risk communication. The social component covers the public's reaction to a warning. This article is mainly concerned with the organizational component of warnings.

Emergency plans specify procedures for standing up personnel, for instance based on different warning levels. Alexander (2015, p. 15) listed as examples a hazard watch phase, where an impact is likely and a hazard warning phase where impacts are very likely or certain. Similarly, there are procedures to stand down staff once an emergency situation has passed. Emergency plans can be developed based on scenarios. A scenario can be constructed based on information about a reference event that occurred in the past. Along with information about present conditions, present vulnerabilities to a hazard are inferred using the reference event (Alexander 2015, p. 18). This is then used to plan for future events. The permanent emergency plan is then also updated based on the consequences of new events. The emergency plan is not meant to cover every contingency. Rather, the plan is extended by additional planning activities as an expected event approaches and during operational response. This involves further decisions to stand up personnel, assign tasks and resources, as well as moving and deploying resources (Alexander 2015, p. 19).

3.1.7 Early Warning

A frequently cited definition is that from the Hyogo Framework, where early warning is defined as providing timely information that enables preparation and response to reduce risk of exposure to a hazard (Basher et al. 2006, p. 2168; United Nations 2005, p. 7). This means early warning assumes that a disaster develops over an "incubation period" and can be anticipated via warning signals (Choo 2009, p. 1072).

On a global level, flood warning only really garnered attention after inclusion as a key priority in the 2005 United Nations Hyogo Framework for action, following the 2004 pacific tsunami (Sukhwani et al. 2019, p. 2). The commitment to early warning by the UN has been reiterated in the 2015 Sendai Framework for Disaster Risk Reduction (United Nations 2015, p. 11). According to a survey conducted by Perera et al. (2020, p. 1) in 2019, the amount of EWS had nearly doubled since 2000. Europe is no exception in this, and the EU Floods Directive (European Union 2007, p. 31) essentially required member states to implement FEWS. Repeated, devastating floods have also driven the uptake of warning systems as technological possibilities increase (Parker & Priest 2012, p. 2927f). Next to endorsement by major institutions, this can also be attributed to improvements of both forecasting and communication technology for disseminating warnings, an increased understanding of large benefits compared to cost and EWS usefulness for adapting to climate change (Cools et al. 2016, p. 117). In Europe, too, FEWS have contributed to lowering loss of life and property to flooding (Parker & Priest 2012, p. 2941-2946).

The UN-ISDR conceptualized Early Warning Systems as comprising of four components, which are 1)Risk Knowledge (data collection and risk assessment), 2)Monitoring and Warning Service, 3)Dissemination and Communication (of early warnings) and 4) Response Capability (planning and preparedness) (UNISDR 2006, p. 2). Most failures in early warning relate to communication and preparedness aspects (Basher et al. 2006, p. 2168). This conceptualization of Early Warning is referred to as “people-centred”, meaning that it’s focus is to protect people at risk (Basher et al. 2006, p. 2174). People-centred Early Warning Systems depart from what Basher et al. (2006, p. 2171-2174) described as the “linear-paradigm” or “end-to-end Early Warning Systems”. While the linear paradigm does highlight the need to connect every element in a warning chain, technical aspects relating to monitoring tend to be the main focus, with less attention paid to response planning or vulnerability modelling. Forecasting experts tend to be the main stakeholder of the system, resulting in difficulties communicating aspects of the model to non-experts, like for instance the meaning of uncertainty, false alarms and needed responses to a warning (Basher et al. 2006, p. 2172f). Modelling a people-centred early warning system, Basher et al. (2006, p. 2174) added administrative actors, communities and researchers, as well as feedback channels to the linear end-to-end warning system. This way, the model also includes activities such as building public awareness, response capabilities and preparedness elements, but also aspects of performance measurement and institutional learning (Basher et al. 2006, p. 2174f).

FEWS also frequently fail to deliver, as they are met with potential shortcomings along every part of the warning process (Parker & Priest 2012, p. 2928-2930). Over recent decades, there have been substantial improvements in the capacity of forecasters to model and predict floods. However, the effectiveness of EWS is hampered because it often does not translate into preparatory actions (Sukhwani et al. 2019, p. 5). Numerous challenges to effective early warning have been identified in the literature. The following section will outline and delimit challenges relating to the institutional aspects of EWS. Dissemination and Communication aspects are identified as the weakest link in most EWS. Literature on EWS, however frequently focusses mainly on the technical components, while attention to communication and preparedness elements is more limited (Cools et al. 2016, p. 117f; Perera et al. 2020, p. 2).

Perera et al. (2020) surveyed challenges in non-technical components of early warning systems. Regarding warning dissemination and communication, they identify warnings reaching limited audiences, people not acting on warnings received and warnings arriving too late for meaningful responses (Perera et al. 2020, p. 3). This can result from Forecasting Centres having no communications officers, communicating data in an inefficient manner or warnings being issued inconsistently because no Standard Operating Procedures exist (Perera et al. 2019, p. 19). Unclear responsibilities along the communication chain, weak working relationships between forecasters and forecast-users and resulting communication issues were also named (Perera et al. 2020, p. 3-4). The forecasters operating the monitoring system, while providing much-needed technical know-how often lack knowledge of response capabilities or preparedness of alert recipients (Perera et al. 2019, p. 18).

Sukhwani et al. (2019) distinguished knowledge, institutional and technology barriers, where knowledge barriers relate to risk awareness across involved actors, technology barriers relate to the monitoring and communication technologies and institutional barriers relate to the effective flow of warnings into stimulating preparatory actions. Based on three case studies, Sukhwani et al. (2019, p. 12) identified institutional barriers, including poor contingency planning, unclear organizational arrangements, inflexible alerting standards or interrupted information flows as the main problem hindering effective functioning and linkages between components of EWS. Knowledge barriers like a lack of risk awareness or confusion about warning schemes were also identified, while technological barriers were less present.

An illustration of unclear responsibilities causing issues for early warning is provided in Dedieu's (2010, p. 4f) description of fuzzy responsibilities in France during a 1999 storm. Meteo-France and French Civil Protection had informally agreed to tolerate a 15% margin of false alerts. The two organizations defined a successful alert differently, however. Alerts were in practice treated as vigilance notices and did not necessarily imply a reaction. The de-facto definition of an alert used, however, is geared toward being actionable for civil protection and evaluates expected damages. Meteo-France issued alerts based on the severity of a forecasted weather event (e.g., the amount of rain). Civil Protection evaluated alerts based on the amount of damage caused and in joint evaluations, this was the definition mainly used. Dedieu (2010, p. 7) characterized the procedure as a “system of vigilance possessing the constraints of an alert system”. As a result of this, the procedure did not account for crucial communication between Meteo-France and Civil Protection agencies and alert recipients sometimes did not know how to react (Dedieu, 2010, p. 5f).

Perera et al. (2020, p. 4) named insufficient, infrequently updated or not implemented contingency plans, coordination issues among implementing agencies, no drills and training, as well as generally low risk awareness as challenges impeding EWS effectiveness. Similar issues are also named regarding response capabilities, like no assessment of evacuation possibilities and low perception of risk leading people to dismiss warnings (Perera et al. 2020, p. 5). Among other things, Perera et al. (2020, p. 7f) recommended clarifying responsibilities in warning and communicating contingency plans and developing the working relationship between forecasting agencies and forecast users.

Cools et al. (2016) examined challenges to effective use of EWS focussing especially on the response capability component of EWS across three cases. For a response to take place, preconditions are that the warning information is understood and usable, responsibilities are clearly attributed, and responsible authorities are prepared to react. This can be achieved, for instance by using alert colour codes based on forecast thresholds, with clear implications. Cools et al. (2016, p. 121) recommended utilizing knowledge of local conditions to fine-tune said thresholds. Following the issuing of an alert, a first response can include triggering an emergency committee coordinating all relevant authorities to plan further steps. Monitoring and using sluices to modify water retention is another possible step (Cools et al. 2016, p. 119f). In estimating the value of flood warnings, Priest et al. (2011, p. 106) assumed evacuations, placing search and rescue crews, and operating flood defences as measures taken by government actors. In addition, they assumed further measures taken by communities, businesses, and individuals mainly to safeguard property.

Given the wide number of issues present in FEWS, during disasters they often do not perform as expected (Parker & Priest 2012, p. 2928). Overconfidence in warnings and misunderstanding of uncertainty surrounding them can lead to mismanagement due to underestimating a threat (Morss 2010, p. 93). When evaluating warning systems, the expected value in terms of lives and property saved is often used as a metric (Pappenberger et al. 2015, p. 279; Priest et al. 2011, p. 102f). To estimate these properties, aside from responses by government agencies, responses by the public are assumed, which often do not manifest strongly (Parker & Priest 2012, p. 2941-2948). Early warnings are frequently ignored by the public, due to low-risk awareness, for instance because of overconfidence in flood defences and low trust in warnings. Another reason are issues with risk communication, like warnings not reaching large parts of the public.

For this reason, forecasting agencies are often concerned about issuing false alarms that could undermine public confidence in warnings (da Silva et al. 2020, pp. 308–311) or trivialize alert levels (Kougkoulos et al. 2021, p. 1965). It can also lead to forecasters being overly cautious and not issuing an alert when there is in fact a danger (Dedieu 2010, p. 19). Threats are sometimes not recognized, because they appear normal to decision-makers. Dedieu (2010) introduced this concept as treacherous risk. A treacherous risk is extraordinary, with no adapted procedures in the warning system existing, leading to a failure of the warning system. The elements making a risk treacherous can relate to characteristics of the warning system within organisational control, but can also be external factors out of an organization's control, like for example relating to physical characteristics of a disaster (Dedieu 2010, p. 7-18).

As FEWS will often only be partially effective, Parker & Priest (2012, p. 2947) warned of solely relying on them to safeguard lives and property. In line with previously discussed literature, this article thus takes the stance that the goal of improving FEWS should be to bolster preparedness aspects of a diversified FRG arrangement.

3.1.8 EFAS and probabilistic forecasts

EFAS is an ensemble prediction system (EPS) for flood forecasting that provides medium-range forecasts (three to ten days in advance) assisting national flood warning systems. EPS are probabilistic forecasts that rather than making a single (deterministic) prediction, provide a set of forecasts. With this probabilistic information, worst cases and most likely scenarios can be identified and used to improve responses (Demeritt & Nobert 2011, p. 128). EPS forecasts also tend to perform better than deterministic forecasts in predicting river floods (fluvial floods) over the medium term (Demeritt & Nobert 2011, p. 129).

EFAS became part of the EU's Copernicus Emergency Management Service, which provides information for emergency response, in 2011 (Smith et al. 2016, p. 314f). Since then, EFAS' forecast performance has improved steadily (Smith et al. 2016, p. 338f) and the userbase of national agencies kept expanding (Smith et al. 2016, p. 315).

EFAS is operated through 4 centres performing different function, each run by different national meteorological services and European institutions. It is managed by the European Commission (Smith et al. 2016, p. 317). EFAS information is not publicly available, to respect the World Meteorological Organization's Single Official Voice principle. Rather, it is disseminated in two ways to national authorities that are responsible to react to flooding. The first is through access to a web platform, which national authorities responsible to warn the public or react to flooding can access after signing the access conditions. The second is through alerts send to EFAS partners, like national meteorological services, via email (Smith et al. 2016, p. 332-335). The logic behind the

SOV principle is to ensure warnings are issued by an authoritative source in a coordinated manner, to avoid a loss of confidence in warnings among the population, due to false alerts or difficulties to verify whether warnings are trustworthy (Silingardi 2019, p. 175). Silingardi (2019, p. 187), described EFAS as the only transnational project that has achieved in implementing the SOV principle.

This paper focusses on the information EFAS provides to national partners through the EFAS platform. Next to allowing partners access to the platform, EFAS produces three types of notifications that are received by partners. A flood alert is produced, if 3 consecutive hydrological forecasts, which are produced twice a day, find that there is at least a 30% probability of exceeding a given threshold. These flood warnings range from low to severe. Another type of alert can be sent, if forecasters think authorities should be informed, even though alert criteria are not met (Smith et al. 2016, p. 334).

The communication of an alert nationally, is then supposed to be handled by national meteorological services communicating with civil protection authorities, in line with the SOV principle (Smith et al. 2016, p. 315). The previous section described significant barriers to making use of flood alerts and forecast information for preparatory action. This is even more so the case for EPS forecasts like EFAS. While uncertainty information can actually increase the value of a warning (Arnal et al. 2020, p. 204-215), there are additional issues to be addressed to incorporate this information into the decision-making process (see cf: Arnal et al. 2020; Dale et al. 2014; Höllermann & Evers 2017; Nobert et al. 2010).

Similar to the general trend in the early warning literature, however, most papers focus on technical aspects of EPS models and fewer papers focus on barriers for preparedness and operational utility to materialize (see for examples Demeritt et al. 2013; Demeritt et al. 2010; Nobert et al. 2010). For EFAS specifically, these articles drew on the early stages of its implementation and pre-operational testing (Demeritt et al. 2013, 2010). For this period, Demeritt et al. (2013, p. 151-153) found that perceptions on EFAS diverged between forecasters across Europe. Few forecasters had experience with own EPS tools. Especially in countries with more legalistic FRM, like Germany, uncertainty information was perceived as difficult to use in issuing alerts (Demeritt et al. 2013, p. 151). Forecasters in these countries expressed issues with EFAS being too coarse, difficult to relate to locally calibrated models and not really needed (Demeritt et al. 2013, p. 151f).

Especially along transnational river basins, EFAS was more appreciated, although only as a pre-warning to raise internal alertness of the forecasting agency, with no earlier warnings or other preparatory actions taken based on it (Demeritt et al. 2013, p. 154). This can also be linked to emergency plans or warnings in national systems being triggered on shorter time horizons than what EFAS alerts can provide (Demeritt et al. 2013, p. 153). As a result, forecasting agencies delayed warnings to civil protection agencies to conform with warning procedures or wait for confirmation by locally calibrated forecasts against a higher warning threshold (Demeritt et al. 2013, p. 154). This reflected that the main organisational concern of these agencies was not flood damage mitigation in the medium-term, but rather immediate responses in the short-term against a high degree of certainty (Demeritt et al. 2013, p. 154f). Some forecasters complained that EFAS lacked accountability and put all the responsibility to handle uncertainty information on the forecaster (Demeritt et al. 2013, p. 155). Another forecaster complained that communicating alerts with uncertainty information would be to pass on that responsibility to Civil Protection Agencies (Demeritt et al. 2013, p. 151), which were generally perceived as unable to utilize such information (Demeritt et al. 2013, p. 155). Recommendations to issue warnings against lower thresholds to mitigate damage collided with institutional concerns to issue false alarms eroding public confidence in the warnings and creating costs and accountability issues (Demeritt et al. 2013, p. 154f). To reap operational value of EFAS alerts thus, there are a number of tensions between the risk of error, blame and flooding (Demeritt & Nobert 2011, p. 146) that need to be resolved.

The literature addressed how to best communicate uncertainty information to forecast users, particularly non-scientists (Demeritt et al. 2010; Höllermann & Evers 2017). Frick & Hegg (2011, p. 300-302) showed, however, that while forecast users tend to appreciate the provision of uncertainty information, that is not enough to lead to its inclusion in routine decision-making or higher quality decisions.

Nobert et al. (2010) drew lessons from how in Sweden, external EPS forecasts have been integrated for operational use by Civil Protection Agencies (CPA). These are to maintain a close working relationship between forecasters and CPAs, deliver tailored training to use EPS to forecast users, involving forecast users in the design of forecast representation and to determine operational options for CPAs to use EPS forecasts (Nobert et al. 2010, p. 73-77).

In Sweden, CPAs are set up decentralized, on a municipal level while flood forecasting is centralized nationally. Alerts are issued with tailored explanations to CPAs and are frequently followed up by direct exchange to ensure correct understanding of the situation (Nobert et al. 2010, p. 74). CPAs are also well informed about developments in forecasting, through regular meetings with forecasting agencies, training to understand the forecasts and the involvement in designing forecast output. This creates a basis for operational demand for improved forecasts (Nobert et al. 2010, p. 74).

The main factor boosting the operational use of EPS forecasts, however, is to link them to operational options and use uncertainty information to improve the response. Uncertainty information is for instance used to weigh risks of different hazards against each other and demands on available staff and resources (Nobert et al. 2010, p. 77). This integration of EPS forecasts and the integration of uncertainty information in decision-making processes is also favoured by an institutional setup geared toward precaution and responsibly of local CPAs for managing uncertainties (Nobert et al. 2010, p. 77).

Morss, (2010) described how flood forecasts impacted management decisions in three cases in the United States. In two out of three cases, warnings were issued and used to prepare for flooding, by placing search and rescue crews in advance and building temporary flood defences. The level of uncertainty around predictions was not communicated in one case, leading to defences being overwhelmed, despite reinforcements being a meter higher than the prediction. Uncertainty was larger than a meter, however (Morss 2010, p. 91-93). Morss (2010, p. 93f) concluded, that forecasts can be used to inform critical planning decisions and resource allocation. As decisions based on false expectations can lead to disaster, predictive uncertainty can help to illuminate different potential scenarios and consider appropriate responses.

The literature review conducted for this paper set out to organize institutional barriers to flood early warning by concepts. The next section summarizes these barriers as problem specifications to then derive Design Objectives for the reference model.

3.2 Problem Specification

The main problem this article aims to address, is identifying and overcoming barriers to utilizing EFAS information inform decision-making for FRM stemming from organizational factors. Some scholars concluded that in FRG, more attention needs to be paid to institutionalized learning (Sawalha 2020, pp. 474–477) and lessons are often not drawn in a structured way (Thieken et al. 2016, p. 9f). A reference model can support such lesson drawing processes and thereby aid partners in evaluating uses of EFAS information.

The sources of barriers to using EFAS in decision-making originate from different levels of FRG contexts. Barriers are based on tensions between different concepts of flood risk and understandings of the goals of FRM. The following section summarizes problems identified in the literature.

The 2007 EU floods directive essentially requires member states to install early warning systems and use risk-based governance tools (European Union 2007, p. 30-34). The literature on early warning, tends to adopt risk-based governance concepts (Choo 2009) or develop recommendations for improving risk-based decision-making (Arnal et al. 2020; Dale et al. 2014; Höllermann & Evers 2017). Principles of risk-based governance are sometimes incompatible with other principles and practices, creating tensions and resulting in only partial adoption of risk-based approaches (Krieger 2013; Rothstein et al. 2011). For instance, the need to justify spatial planning decisions on private property, makes it difficult to explicate uncertainty around the effectiveness of structural flood defences in Germany (Krieger 2013, p. 247). The right to equal protection for everyone sits uneasily with tolerability thresholds for failure scenarios (Albano et al. 2015, p. 2720f). Similarly, inconsistencies in the mode and goals of risk communication due to unresolved value conflicts (Demeritt & Nobert 2014) can result in ineffective practices. In addition, to avoid blame-shifting in implementing risk-based governance, rather than just redistributing responsibilities, special attention needs to be paid to delivery processes (Butler & Pidgeon 2011, p. 546). These tensions in the bases of FRG translate to tensions in aspects of FRM, including early warning.

While feedback loops for institutionalized learning are not a new recommendation in the literature on FEWS for a while (Basher et al. 2006, pp. 2173–2176), lessons from past events have often not been drawn in a structured and consistent way (Thieken et al. 2016, p. 9f).

Different views on resilience embedded in existing FRG arrangements relate to what FRM strategies are emphasized, potentially implying trade-offs and path-dependencies (see cf: Hegger et al. 2016; Wiering et al. 2018). Much of the literature on FRG moves from the viewpoint that structural flood defences, due to climate change and development pressures are increasingly prone to failure (Driessen et al. 2018, p. 12; Hegger et al. 2016, p. 9). FRG tended to focus on flood defence by means of structural measures and as a result a dominance of organisations focussed on flood defence still prevailed in some European countries. Legislation and operational procedures may then be adapted to managing structural measures, as for instance the historical focus on hazard-information over socio-economic damages in German flood management may be an example of (Krieger 2013, p. 249f). Development of areas protected by these defences, combined with interests of existing institutions focussed on maintaining them, creates path dependencies and at the same time increased vulnerability to failure. To cover different stages of flooding and aspects of resilience, the literature calls for diversifying FRM. The existing arrangements, however, limit and steer reform initiatives (Matczak et al. 2018; Wiering et al. 2017). If flood defence is the dominant approach, this can lead to trade-offs weakening preparedness (Hegger et al. 2016).

In realizing flood preparedness strategies, Dieperink et al. (2016, p. 4474) outlined clearly attributing and linking responsibilities of forecasters, warning disseminators and forecast users, to create accurate warning systems and emergency plans as challenges. Good emergency plans need to manage communication through communication protocols, procedures and clear roles (Alexander 2015, p. 9f). For the early warning system this necessitates strategies to communicate scientific monitoring information effectively to non-scientists (Basher et al. 2006, pp. 2172–2176).

Potential issues with realizing contingency plans can include incomplete assessments, for instance of evacuation routes (Perera et al. 2020, p. 5), poorly implemented and infrequently updated plans or coordination problems and a lack of drills or training (Perera et al. 2020, pp. 3–5; Sukhwani et al. 2019, pp. 10–12).

Issues in capitalizing on early warning can then result from numerous sources. Unclear communication or decision responsibilities (Perera et al. 2020, p. 3; Sukhwani et al. 2019, p. 12), inflexible alerting standards, interruptions in the information flow (Sukhwani et al. 2019, p. 11) and forecasting centres lacking communication capabilities or communication protocols can lead to problems in issuing warnings. Communication problems can also arise due to a weak working relationship between forecasters and forecast users (Nobert et al. 2010, p. 73f; Perera et al. 2020, p. 3) and forecasters being unaware of response capabilities of forecast users (Perera et al. 2019, p. 18).

Warning information needs to be understood, usable for decisions, and responsible authorities ready to react to it, through triggering planning decisions linked to the warning (Cools et al. 2016, pp. 120–121). Warning information thus needs to be linked (Alexander 2015, pp. 12–15) and compatible with plans. A planning focus on the short-term can lead to contingency plans unfit to make use of longer lead times (Demeritt et al. 2013, p. 153).

This also applies to the use of probabilistic information. Communicating forecast uncertainty has the potential for improved value for decision-making, for instance by highlighting potential worst-case scenarios (Demeritt & Nobert 2011, p. 128) and improved resource allocation (Nobert et al. 2010, p. 76). If uncertainty information is misunderstood or not communicated, it can lead to mismanagement (Morss 2010, p. 92f). The mere provision of uncertainty information may not suffice, however, to improve decision quality (Frick & Hegg 2011, p. 301-303). Uncertainty information needs to be both communicated, understood and procedures need to allow incorporating it into decision-making (see Arnal et al. 2020, pp. 214–219; Dale et al. 2014, pp. 4–8) for it to improve decisions made. This resonates with Nobert et al.'s (2010, p. 76f) finding that it was important to tie operational options to probabilistic forecasts for Civil Protection Agencies to use it. A lack of room for risk-based decision-making, unresolved accountability questions and a lack of communication and planning around EFAS (Demeritt et al. 2013, pp. 153–156), also posed barriers to its operational use.

These barriers resulted in EFAS frequently serving mainly as a pre-alert, boosting internal alertness (Demeritt et al. 2013, pp. 153–156). Additional lead time was thus often not capitalized on, as planning only incorporated warnings from local forecasts on shorter lead times against higher certainty (Demeritt et al. 2013, pp. 154f). Given unresolved accountability questions and no possibility for using probabilistic information in decision-making, some forecasters felt that accountability was being dumped on them. Uncertainty information was also not capitalized on in some cases, as CPAs were viewed as unable to make use of probabilistic information provided by EFAS. Passing an EFAS alert on was then perceived as putting all accountability on forecast users (Demeritt et al. 2013, p. 155f).

Some of the barriers to utilizing early warnings identified in the literature go beyond decisions by authorities and are not addressed by this paper. These are nonetheless crucial topics for the effectiveness of FEWS. Most importantly issues with risk communication toward the public, resulting in low warning response or warnings not reaching segments of the population (Parker & Priest 2012, p. 2941-2943; Perera et al. 2020, p. 3) are not addressed in this paper. Similarly, fundamental challenges to early warning systems, like treacherous risks that the warning system is not capable of detecting (Dedieu 2010) or maintaining high risk awareness and preparedness over the long term (Parker & Priest 2012, p. 2946-2948) need to be kept in mind. This may highlight the benefits of diversified FRM where the weaknesses of early warning systems can be compensated by other strategies (Parker & Priest 2012, p. 2943-2946), like for instance pro-active spatial planning measures (Hegger et al. 2016, p. 7-10).

3.3 Design objectives

Following Peffers et al. (2007), Design Objectives for the reference model were inferred from problem specifications. In the context of the first iteration of the DSR cycle, this section corresponds to design and development of Design Objectives. Design objectives for the reference model were constructed as requirements on what aspects of the early warning process the model should depict. Each aspect is derived from identified problems, as outlined in the following section.

EFAS information can aid the monitoring components of FEWS, but this flood warning information needs to be matched with institutional capabilities to act on warning information. Organizational barriers to capitalize on early warning information and EFAS have been identified in the literature. While the literature review highlighted numerous barriers to the effective functioning of FEWS, it also highlighted conditions for achieving working institutional capabilities. Still, they comparatively received less attention than technical components of FEWS (Perera et al. 2020, p. 2). Specifically regarding EFAS, the articles identifying barriers to utilizing EFAS all stem from its pre-operational phase and are now almost a decade old (Demeritt & Nobert 2011; Demeritt et al. 2013).

Few models incorporating organizational elements of FEWS could be identified in the literature review. Two system models describing dynamics within EWS more generally were identified (See Basher et al. 2006, p. 2175; da Silva et al. 2020 for system models of FEWS). No reference models focussing on processes within flood warning organizations were found. Following vom Brocke & Maedche (2019, p. 13) if few existing design entities address a given problem, developing a new entity, in this case a reference model is appropriate. The model can aid attempts to improve institutional capabilities to capitalize on EFAS alerts where there are barriers to doing so. The following section introduces the necessary components for the model to depict based on the identified problems.

One of the most frequently identified needs for effective early warning was assigning clear responsibilities, both for communicating and making decisions (Alexander 2015, pp. 10–13; Perera et al. 2020, pp. 3–6; Sukhwani et al. 2019, p. 12). Accountability around those responsibilities may also not be clarified (Sukhwani et al. 2019, p. 12) and consistently defined (Dedieu 2010, p. 5f). The model thus needs to depict responsibilities for clear communication and decision responsibilities and show accountability is defined and assigned.

The literature also highlighted the need to clarify processes, to avoid merely redistributing blame (Butler & Pidgeon 2011, p. 546). In the case of early warning, on the organizational level, these processes revolve around communicating risk information and taking a warning decision (Alexander 2015, p. 13).

The literature identified many potential barriers to effective communication in EWS. Warning information needs to reach users, reach them in time (UNISDR 2006, p. 6) while avoiding interruptions in the information flow (Sukhwani et al. 2019, p. 11f). Information needs to be complete, uncertainty information should be provided (Morss 2010, pp. 92–94). Information needs to be communicated effectively in a way that ensures it is understood (Cools et al. 2016, p. 119f). This includes presenting warning information appropriately, but also realizing necessary support like trainings and a strong working relationship between forecasters and forecast users (Nobert et al. 2010, pp. 73–76). The model thus needs to depict communication flows to ensure uninterrupted, complete and effective communication.

Finally, literature showed that merely providing and explaining information does not necessarily lead to decision-making. Forecasts need to be linked to contingency plans (Alexander 2015, pp. 12–15; Cools et al. 2016, pp. 120–121). Operational options need to be identified to use uncertainty information as well (Nobert et al. 2010, p. 76f). This implies that decisions and procedures also need to be compatible with forecast information for it to impact decision-making. For instance, if uncertainty information cannot be indicated in warnings it is not utilized in decisions (Demeritt et al. 2013, p. 155f). Similarly, if plans operate on shorter time scales, additional lead time provided by warnings is not utilized (Demeritt et al. 2013, p. 153). Whether information can be used to issue warnings also includes what level of detail is necessary for which decisions as well as setting appropriate certainty thresholds (Choo 2009, pp. 1079–1081). Appropriate decision procedures to utilize uncertainty information are also needed (see cf: Arnal et al. 2020; Dale et al. 2014; Frick & Hegg 2011). The model thus needs to depict decisions and procedures to ensure warning information is linked to decision-options and is compatible with plans and procedures.

To structure the problem specification, this paper drew on Sukhwani et al's (2019, p. 6) description of institutional aspects underlying EWS to group identified barriers to make use of early warnings, where institutional aspects ensure the flow of timely information between FRM actors and stimulate necessary responses. Institutional barriers by this definition can relate to three things: First, responsibilities and accountability of actors in FRM, the flow of timely information, and how response actions are considered and planned, here referred to as decisions and procedures.

3.4 Demonstrating Design Objectives

Following Peffers et al. (2007), a demonstration of the Design Objectives was carried out to make sure they fulfil the purpose of covering all the issues identified during the literature review. As a demonstration of the Design Objectives, showcasing that they cover the problems identified in the literature, a graph was constructed, showing how the identified problems specifications correspond to Design Objectives. It can be found in Annex **Fehler! Verweisquelle konnte nicht gefunden werden.**.

3.5 Evaluation of Design Objectives

An evaluation of the Design Objectives was conducted, in the form of a first series of four interviews, during which the Design Objectives were presented to model stakeholders. Interviewees were asked about the Design Objectives, to describe the elements of the Design Objectives for their organization, as well as anything else they considered relevant. **Fehler! Verweisquelle konnte nicht gefunden werden.**shows a visualization of the preliminary Design Objectives which was also sent to interviewees for the first interview series.

The purpose of the reference model is to inform processes aimed at improving or establishing the use of EFAS information for decision-making by model stakeholders like EFAS centres and EFAS partners. As such, the stakeholders of the model are practitioners as well as academic experts on FEWSs. Practitioners were further distinguished based on the literature review to include forecasters both nationally and at EFAS, as well as forecast users.

This stakeholder group is by no means monolithic, however. EFAS partners operate in diverse settings, that are not static, but often changing. This is apparent when comparing the Flood Risk Management Plans (FRMPs) governments submitted in 2015 under the 200t Floods Directive. While local or regional authorities were involved in drafting FRMPs in 26 of 28 countries, Civil protection authorities were involved in 21 countries and flood warning or defence authorities in 18 countries (European Commission 2021, p. 38f). What strategies measures focussed on, how they were prioritised and the implementation progress across strategies varied widely (European Commission 2021, pp. 76–97). This should serve as an illustration that reform agendas are set by varying constellations of organizations and that preparedness and early warning are of differing importance across Member State’s FRMPs. It should be noted, however, that this is an imperfect measure to compare countries, given that it is unclear to what extent the measures are comparable, for instance in monetary terms. Countries also created these plans moving from different base states, few measures to establish early warning systems could both imply a lesser focus on early warning or the existence of very established early warning systems.

The goal of the interviews was twofold: To evaluate and sharpen the Design Objectives, and to provide a knowledge basis for the second DSR iteration to design the reference model. First, potential interview partners, both practitioners and academic experts were selected. Next, interview goals and an interview guide, consisting first of a discussion basis for the interview were created. Finally, interviewees were contacted via email for a video-interview using Zoom.

3.5.1 Interviewee selection

The following sections outlines the different steps taken and the materials considered for the selection of initial interview partners. For initial interviews, EFAS centres, national forecasting agencies and academic experts were contacted. Academic experts were contacted based on the literature review. In selecting national forecasting agencies, the initial focus was on contacting forecasting agencies in countries with significant flood risk and a strong focus on early warning and preparedness, to ensure relevance of the problem to interview partners. Given the difficulty comparing countries based on flood risk metrics or the FRMPs, national forecasting agencies were ultimately contacted based on the literature review. Following the evaluation, the focus was shifted to identify different practices of using EFAS across partners, to highlight alternatives and thereby aid in evaluation of current and potential uses. The selection of interview-partners was thus expanded to cover types of EFAS partners not covered in the model so far, including not only forecasting agencies but also civil protection agencies. Additional interview partners were contacted based on insights from the initial interviews.

As interview partners for the evaluation of Design Objectives, forecasters, forecast users and scientific experts were contacted. Academic experts were contacted based on the literature review. The interviews are presented in an anonymized fashion throughout the thesis and referred to in general terms.

Based on the EFAS webpage (EFAS.eu), centres performing operational tasks within EFAS were contacted making up two of the initial interviews. It should be noted, that some EFAS centres have a dual role of acting both within EFAS, as well as performing as national forecasting agencies. This was considered an advantage for the interview, as it allowed to cover this dual perspective. These interviews focussed on how EFAS is used nationally and connects to the functions performed by the forecasting agency and whether the preliminary Design Objectives were considered relevant and complete.

3.5.2 Evaluation results

The first iteration of interviews consisted of five semi-structured interviews conducted between the 11th and the 19th of April 2022. For this iteration of interviews, a short interview guide was used. The interview guide consisted of several open-ended starting questions and a visualization of the Design Objectives to order the general topics to be covered. During the interview, follow-up questions were asked to move from general questions to more specific topics. Interviewees were contacted via email for a zoom interview and provided with the visualization of Design Objectives. Upon request the list of starting questions was provided as well. Starting questions were adapted to the type of interviewee and revised iteratively across interviews. Follow-up questions were also sometimes tailored to introduce issues that came up in previous interviews.

The following section presents the results of the evaluation and justifies adjustments made to the objectives. The goal of the evaluation was to assess whether the Design Objectives included the relevant components to depict how national partner institutions integrate

EFAS into their warning process. Interviewees were thus asked to describe the warning process, how EFAS tools were used and directly whether they considered the Design Objectives relevant and complete. Interviews were analysed using rudimentary open coding based on the preliminary Design Objectives to determine which aspects of the Design Objectives a given interview section was relevant for. The general components were rephrased, relevant issues to be addressed were specified more in depth and issues that go beyond the use of EFAS excluded.

Conclusions are presented across the three general aspects of the aspired model and explained drawing on the conducted interviews. First, Roles and Responsibilities, both within EFAS and for EFAS partners are introduced and issues to be modelled discussed. Following that, communication flows between EFAS and partners and communication flows between partners and other national actors are presented. Finally, decisions and procedures for dissemination of notifications and support to user groups, and decisions and procedures by partners for use of EFAS information are introduced. Finally, a graphical overview of the conclusions is presented, mapping the aspects to be modelled.

While interviewees considered the issues in the objectives relevant, they highlighted that the objectives were phrased as to describe a perfect situation. One manager at a forecasting agency said, that different national system would fulfil any of the objectives to varying degrees but never perfectly. As a result, the Design Objectives were rephrased for the model to describe different EFAS partners' usage of EFAS along the three aspects, responsibilities, communication flows and decisions and procedures. This way, the model aims to show in which ways EFAS information can impact processes in national flood early warning and where issues can occur.

Roles and Responsibilities

The Design Objective to depict "clear communication responsibilities" was changed to "depict roles in communicating EFAS information". Interviewees described disseminators on the side of EFAS, as well as recipients of EFAS notifications or users of the EFAS platform. It also involves indirect recipients, who receive EFAS information indirectly, in the form of forecasting products, for which EFAS information was considered. These should be depicted in a general fashion to capture relevant differences in terms of how EFAS information is passed on into different processes.

In a similar vein, the Design Objective "clear decision responsibilities" was changed to "depict roles involved in using EFAS information". Interviews described decision-makers at EFAS partner organizations who use EFAS for different decisions, like assessments feeding into national products, contacting other parties, or triggering response decisions.

The Design Objective “Accountability consistently defined” was dropped, as this is by definition not consistent with regards to EFAS. Both EFAS and EFAS partners internally define accountability to provide their own services. However, neither is EFAS accountable for notifications beyond internal procedures, nor are partners necessarily accountable for how they use this information. As a result, an interviewee at an EFAS centre explained, EFAS centres have little information about how exactly partners use EFAS products because this goes beyond their mandate. The model should therefore depict different constellations of how partners make use of the information.

Communication

The objective “Uninterrupted information flow” was changed to “depict communication channels for EFAS information to end users”. Interviewees described communication channels into which EFAS information is fed after being received and further processed nationally. These should be depicted again, in a general fashion to highlight differences in where EFAS information is passed on to. This could include national forecast products that EFAS information fed into, or notifications sent to subsequent authorities, like civil protection or local governments.

The objective “effective communication” was changed to “depict advice and support activities”. Interviewees described activities to explain forecasts and aid forecast users interpreting it as part of communication channels. This can involve translating received information for other agencies, answering questions and intense contact to explain information and possibly support decision-making.

The objective “complete communication” was changed to “depict what information is being communicated”. In interviews this involved the communication of hazard/hydrometeorological information or impact information, as well as differences in whether uncertainty is communicated or not. In addition, the timescales for which information is being communicated was discussed with EFAS information being used at different lead times.

Decisions and procedures

The objective “decision-options to use warning information determined” was changed to “depict decision-options to use EFAS information”. Interviewees described using EFAS as part of an assessment, comparing it to other information, as a pre-warning to prevent vacancies, as well as issuing warnings connected to response actions.

The Design Objective “plans and decision-procedures compatible with warning information” was changed to “depict what information is being used”. This means, that the model should show, for the different decisions interviewees described, which information is considered. Interviewees described for instance using EFAS in conjunction with other information sources as well as considering different parts of these information sources, like whether uncertainty information is used for decisions or not. **Fehler! Verweisquelle konnte nicht gefunden werden.**shows a visualization of the final Design Objectives.

In summary, interviewees at EFAS partner organizations described EFAS as one source of information out of a wider selection of information sources. EFAS partners receive EFAS notifications at different frequencies. The extent to which the tool covers the catchments monitored by a particular partner differs as smaller catchments are often not yet included. EFAS also does not cover all sources of flooding a partner may be concerned with. As a result, the extent to which EFAS information is fed into forecasting products or decisions made by national partners differs as well. The model should highlight general modes of utilizing EFAS information partners rely on. It can aid potential new partners when assessing how the system might fit into their work and old partners, re-assess the way they are currently making use of the system, as for instance EFAS information becomes more granular and increasingly includes smaller catchments as well.

Another outcome of the evaluation was to widen the knowledge base for constructing the model by including interviewees from Civil protection organizations, as well as additional national forecasting agencies.

The evaluated and updated Design Objectives were used to start the second iteration of the DSR Cycle, by constructing a framework for the reference model.

To construct the model, four more interviews were conducted. Additional interview partners were selected based on recommendations mentioned in interviews and CPAs were contacted for these interviews.

In the following section, the second Design Cycle Iteration is described. First, initial decisions on a modelling language and construction techniques are explained. Following that, a general frame for the model is developed drawing on initial and additional interviews. Finally, the model evaluation is explained, and the final model described.

4 Design Science Cycle Iteration 2: Designing a reference model

The following chapter describes the second design cycle iteration, during which the reference model describing the use of EFAS products in national FEWS was designed, demonstrated, and evaluated.

The first part of this chapter deals with selecting a modelling language for the reference model based on the Design Objectives. Following that, a general frame for the reference model is constructed by deriving general functions EFAS is used in from the conducted interviews and identifying general elements of those functions which differ across EFAS partners.

Following that, the demonstration of the model and its evaluation are outlined. The final model, including changes made during evaluation, is described at the end of this section.

4.1 Reference Modelling and Modelling Language

The following section discusses different process modelling languages and justifies the choice made in this article, to model different uses of the EFAS platform through event-driven process chains (EPC). Since no reference process models could be found in the literature review addressing institutional components of early warning systems, interviews from the first DSR iteration as well as the literature from two related fields were consulted. The first is the use of process modelling in Disaster Response Management (DRM). Since the use of process modelling is not very established in this field yet and faces challenges, the article in addition draws on the use of process modelling in public administration more generally.

Following the identification of several modelling languages, their strengths and weaknesses were considered and a design choice to use the extended EPC was made.

4.1.1 Process Modelling in Public Administration

The following section outlines how process modelling is applied and which modelling languages are commonly used in public administration. In public administration more generally, process modelling has found widespread application. In a survey among German administrative organisations in 2014, most respondents reported continuously working on process management (Detemple et al. 2014, p. 25). Process modelling is used to make the different activities performed within an organization more transparent and can be useful for documentation, knowledge management or reorganisation (Halsbenning et al. 2019, pp. 245–249). In this paper, process modelling is used to create a reference model of how EFAS is used by national partners.

In German administration, Detemple et al. (2014, p. 32), found the PICTURE approach, the Business Process Modelling Notation (BPMN) and the extended Event-driven Process Chain (EPC) to be the most frequently used process modelling languages.

While DRM lacks a domain-specific process modelling language, the PICTURE approach represents a domain specific modelling language for public administration (Becker et al. 2007). PICTURE distinguishes 25 different process building blocks representing typical administrative processes with different attributes. Thereby, PICTURE reduces complexity, ensures a similar degree of abstraction across different models, and can improve the clarity of process models but is less flexible and detailed than the other two modelling languages.

BPMN is the most widely used process modelling language in many domains (Halsbenning et al. 2019, p. 252). It allows depicting a variety of different events and activities and their sequence, depicting decisions and parallel activities through connectors, as well as different roles and organizations involved in the form of process pools and lanes. It allows for flexibly depicting detailed processes and is well suited for process automation.

EPCs are an older process modelling language, that depicts activities as an alternating sequence of events and functions, connected by a control flow (Halsbenning et al. 2019, pp. 250–253). In addition, EPCs allow adding elements for roles and organisations, as well as systems and information connected to functions. EPCs, like BPMN are a very flexible form of process notation. EPCs have fewer elements than BPMN and are as a result less expressive but also less complex.

4.1.2 Process Modelling for DRM

There have been efforts to use process modelling in emergency management and planning. As such, this literature focusses on the potential for process modelling to support planning and coordinate resources or response teams. The literature examining the use of BPM for DRM moved from the idea that identifying procedures is important for improving support to rescue organizations (Peinel et al. 2012, p. 1).

Due to the involvement of many different organizations, resources and parallel activities, disaster response management is complex and involves challenges that BPM seems suitable for (Hofmann et al. 2015, pp. 966–968). However, as different authors noted, process modelling was not typically established in disaster response management as of yet (Betke & Seifert 2017, p. 1311f; Peinel et al. 2012). There are a number of domain-specific challenges, however, that complicated the use of BPM in Disaster Response Management.

Challenges for the use of process modelling in DRM include modelling languages lacking appropriate terminology and tools being difficult to use for stakeholders in DRM (Peinel et al. 2012, pp. 3–5). They can also include problems regarding a lack of coordinating processes or information management across DRM organizations or even a lack of response planning (Peinel et al. 2012, p. 8). Studies did however make recommendations and identify requirements, some of which are relevant in the context of this article as well.

Much of the recommendations for DRM focussed BPM made in the literature focussed on aspects of operational emergency management, like automating certain tasks and matching specific resources (Hofmann et al. 2015, pp. 973–976). This article does not aim to develop a process model for operational use, but rather a more abstract reference process to examine and evaluate existing systems and serve as input for potential redesigns.

De Leoni et al. (2011, pp. 51–53) matched the phases of the Business Process Management Cycle to the Disaster Management Cycle, grouping the preparedness phase with process design. Recommendations that relate to process design are considered potentially relevant and are discussed in the following paragraphs.

Peinel et al. (2012, p. 4-6), noted that due to planning uncertainty, emergency managers, prefer “process skeletons”. Following this, (Hofmann et al. 2015, p. 971) recommended predefining abstract models or model fragments. These can provide a general frame, with parts to be filled out based on the situation, rather than complete models that are overly detailed.

Hofmann et al. (2015, p. 973f) also recommended providing tailored business process management systems capable of automatic process execution. At the same time, Peinel et al. (2012, p. 3) noted that features to allow for automatic process-workflow execution often add unnecessary complexity to planning processes not meant to yield a process for automation. The planning process could become more complicated if the tool requires more details than ordinarily needed.

Hofmann et al. (2015, p. 972) recommended using modelling languages that are easy-to-understand and visualize, and that allow depicting all relevant elements. Commonly used Business Process Modelling languages, like BPMN or the EPC were developed for use in a business context. Emergency management organizations typically had their own terminology and operational objectives. BPM languages do not always allow for sufficiently adapting terminology to fit these contexts. They also did not always allow for representing objectives and progress toward them sufficiently (Peinel et al. 2012, p. 3). The EPC has also been used to model disaster response management processes for fire brigades in Germany (Hussung et al. 2020). The EPC was described as an adequate choice due to being easily understandable, given the limited amount of modelling elements, as well as sufficient flexibility, allowing to model main- and sub-processes.

To address the lack of a domain-specific modelling languages, extensions for existing modelling languages have been designed. Betke & Seifert (2017) proposed an extension for BPMN. The extension is focussed on describing operational disaster response processes, by allowing for instance for the description of different resources, their status, mobility as well as user's expertise levels.

4.1.3 Choice of Modelling Language

During three of the initial five interviews, the ones with practitioners, a question about organizational practice and individual experiences with process modelling was included. None of the interviewees reported experience with process modelling. However, some organizations engaged in workflow management, using collaboration tools, like Jira and Confluence to coordinate tasks across organizations. Another way of defining tasks was through textual descriptions of procedures and scheduling.

The Extended EPC was chosen as the modelling language for the reference model proposed in this paper. This is because it uses a more limited set of elements, reducing complexity and making them more similar to the workflows reported during interviews.

EPCs are sufficiently flexible to depict the different uses of EFAS described in interviews at an appropriate level of abstraction. It can depict the relevant elements, roles, communication flows and decisions and procedures. In addition, using EPCs avoids introducing unnecessary requirements aimed at process automation or adding more details than needed potentially reducing reusability. Both standard and extended versions of BPMN would introduce elements that go beyond what is necessary to describe the uses of the EFAS platform by EFAS partners.

In addition, EPCs were already used to model processes in DRM (Hussung et al. 2020). The model would thereby be more easily expanded or reused as an EPC, making it an appropriate choice for reference modelling and for satisfying the principle of language adequacy (Schuette & Rotthowe 1998, p. 246f).

4.2 Construction techniques and the Event-driven Process Chain

EFAS is provided to all partners in the same way. The use of the platform differs across partners, however. Based on interviews, general functions where EFAS is used that are performed in different ways can be distinguished. Instantiation allows for modelling different alternatives across EFAS partners. Aggregation is helpful in ensuring the model fulfils the principles of proper reference modelling following Schuette & Rotthowe, (1998, p. 248f), by making the model clearer and more systematically built.

The elements of the EPC and how the reference model construction techniques are represented in it, are explained in detail in the following paragraphs (see Becker et al. (2012, pp. 15–20) for an outline of the EPC). For this thesis, the SAP Signavio Web Editor was used to construct the reference model EPCs. **Fehler! Verweisquelle konnte nicht gefunden werden.Fehler! Verweisquelle konnte nicht gefunden werden.** is a visualization of what each EPC element looks like in the SAP Signavio Web Editor. The EPC describes processes as an alternating sequence of events and functions. In addition, elements describing roles performing functions, systems used therein as well as information used or created can be added. The sequence of events and functions depends on a control flow indicated by arrows and is steered through logical operators.

Events indicate things that happen during a process, like a certain daytime or receiving a call, or the status of a process, like a certain task being finished. Events are depicted as a purple hexagon. Functions are tasks that are performed during a process, like for instance answering a call. Functions are depicted as a green rectangle.

Functions and Events are connected by a control flow, which is represented as a black arrow. EPC models always flow down, loops are represented by reusing events in the process. The sequence of events is steered by logical connectors that need to be used according to syntactical rules. These are the XOR connector, represented by a circled X, the AND connector, represented by a circled inverse V and the OR connector, represented by a circled V. The XOR connector splits or merges into exactly one path and represents exclusive decisions. The AND operator splits and merges into all connected paths in parallel. The OR operator is used when one or more paths are taken or merged.

IT Systems, like the EFAS web platform, can be assigned to a function with a line, indicating that they are used for that function. IT systems are depicted as a blue rectangle. Functions can be assigned roles, for instance a national flood forecaster, or organizations, like for instance an EFAS partner organization, indicating that they are performed by those respective roles or organizations. Roles are depicted as a yellow rectangle, while organizations are depicted as a yellow ellipse.

Information, like EFAS information, a rainfall forecast or a forecasters confidence in a forecast, can be assigned to functions to indicate it is used or created as part of that function. Information is depicted as a grey shape.

Process interfaces indicate a link to another process in an EPC. Process interfaces are depicted as two overlapping white rectangles.

Instantiations were depicted in the model by defining a general process and connecting functions that vary across EFAS partners with sets of instantiations depicting the different ways in which they are performed. To clearly highlight the connections of the instantiation to the general process, instantiations have start and end events that are present in the general process. The other construction technique employed in the model is aggregation and is visualized through process interfaces pointing to processes being reused. This was used in designing the highest aggregation of the model, as well as for reusing the dissemination process in the warning and forecasting and in the pre-warning process.

4.2.1 General Frame Construction

In the following section, a frame is developed for the model, outlining three general uses of EFAS, as well as characteristics of national arrangements that define different instantiations of functions in the reference model. First, the involved roles and responsibilities, communication flows and decisions and procedures are discussed both on the side of the EFAS consortium and the partners. Following that, the model frame is developed distinguishing general functions EFAS information is used in by partners. The frame distinguishes three main functions with several elements that are outlined here. In addition, the depiction of each element in the EPC is explained.

Roles and responsibilities

The relevant roles for the model, which are performed within national partner institutions were determined to be national flood forecasters, emergency managers and meteorologists. In the following, first the organizational constellation is introduced and the roles within it, on the side of the national partners explained. Processes on the side of EFAS were not depicted in the model. This decision was taken because the model focusses on the use of EFAS by national partners, and the interface of EFAS is the same with each partner. In addition, EFAS mandate strictly ends once information is disseminated, forming an appropriate starting point for a model showing how this information is used by national partners.

A manager at an EFAS centre outlined the functioning of EFAS. EFAS is a centre consortium, with roles distributed across four centres. The European Commission's Joint Research Centre is responsible for the overall management and new developments. EFAS operational system was outsourced to different centres, including the ECMWF as a computational centre, a hydrological and a meteorological data collection centre and a dissemination centre, run by three national forecasting agencies, the Dutch Rijkswaterstraat, the Swedish Hydrometeorological Institute and the Slovak Hydrometeorological Institute. The dissemination centres are responsible for sending EFAS notifications to partners as well as creating a daily report for the European Response Coordination Centre (ERCC). They also function as a service desk for all national partners. Dissemination centres offer the opportunity to schedule trainings to partners, which are held on-site at the partner institution and can also be accessed online as a webinar. Each dissemination centre determines forecasters on duty, with one centre serving as lead partner each day, performing the day-to-day dissemination tasks. Each centre is responsible for a certain area covered by EFAS. The model's starting point is then after this dissemination process, when EFAS notifications and the latest EFAS information reaches partners.

From EFAS point of view, there are two types of national partners. The first are full partners. Any institution with a national or regional mandate to issue warnings to the public can become a full EFAS partner. Full partners are usually specialized national hydrometeorological agencies, sometimes within ministries or other parent organisations and sometimes with wider responsibilities for water management. In some cases, it can also be a purely hydrological service, in close contact with a separate meteorological agency. In other cases, the responsibility to issue warnings lies with authorities responsible for civil protection, advised by a specialized agency. This can be regional or national civil protection organizations. In addition to full partners, there are also third-party partners. Third party partners can not directly request access to EFAS information, but only through a full partner that grants them access to the system. Third party partners can be a range of different actors, including again authorities with a responsibility for civil protection, local authorities, meteorological agencies, but also others, like railway agencies. For the reference model, specialized hydrometeorological or hydrological and meteorological agencies and authorities responsible for civil protection and their interplay were considered. Within hydrometeorological agencies EFAS is accessed by national flood forecasters, which are typically hydrological experts. Because hydrological forecasts rely on rainfall forecasts, meteorological products and meteorological experts also play a role. They may be part of the same organization, in a different department, or work for a separate meteorological organization.

Within authorities responsible for civil protection, national warning information and in some cases EFAS directly, is accessed by emergency managers. Depending on what authorities carry out civil protection responsibilities this can include emergency management and planning experts, engineers, or mayors. They will be referred to as emergency managers, as that is the role they act in when responding to flood warnings.

Communication flows

The communication flows identified in the model are EFAS notification emails, the EFAS web platform, as well as national warning emails, web platforms and phone calls. Phone calls include regularly scheduled calls between authorities, as well as calls made upon sending or receiving a warning. The model depicts communication flows in the day-to-day operations of EFAS partners. There is also communication that occurs on a less regular basis, like for instance the EFAS trainings, monthly bulletins or annual meetings which are not depicted in the model. Another communication flow that is not depicted is whether partners provide feedback to EFAS notifications. This decision was made because determining the processes on how the information for this feedback is collected would have expanded the scope of the thesis too much. Therefore, they could not be depicted in a way covering all aspects of the Design Objectives for the EFAS partners included in the interviews. The less regular communication flows and the feedback channels are still outlined and discussed as they are important to characterize the relationship between EFAS centres and EFAS partners.

EFAS information is communicated to partners through two pathways. Day-to-day dissemination of notifications is performed through sending emails containing basic information. Partners can access EFAS via a web-tool, displaying all EFAS information. Notifications are sent once a prediction fulfils certain criteria and are not updated. Rather, partners can follow the evolution of a notification in the web tool. A project manager at an EFAS centre explained that textual information in the email is limited, and it is made clear to partners that they should view notifications in the web tool. Notifications also include information on the forecaster who issued them who can be contacted for support through a functional mailbox, checked by the forecasters on duty, to provide assistance in case partners have any questions.

Aside from the operational communication flows, additional communication flows include the trainings partners can schedule, monthly bulletins communicating among other things changes to EFAS, training webinars that are uploaded to the EFAS webpage and an annual meeting to discuss changes to the system with partners.

Partners have several pathways for providing feedback to EFAS notifications. Feedback can be provided on sent notifications, through a functionality to report missed events and through an annual survey. In addition, more detailed feedback on selected events is analysed in detailed assessment reports that are compiled annually.

Communication flows of information from EFAS partners on the national level include the dissemination of forecasts and warnings to other authorities and the public through webpages and emails as well as interpretation or decision support through phone calls, meetings or participation in bodies convened in case of certain flood emergency situations.

EFAS Partners pass on different information to other organizations. Generally, information communicated to emergency managers by flood forecasting agencies includes when and where to expect peaks, and the expected duration of a flood event. Between interviews, there were differences in whether hydrological information, like expected discharge values or expected water levels, or impact information, like areas expected to be flooded and associated damages, were communicated. If impact is communicated, additional tools showing postprocessed model outputs, like for instance a layer on the EFAS platform or partner's own models can be used. A flood in a highly populated area would then imply a higher alert level, than a flood in an area that is largely empty. Communicating impact can also involve gathering additional information by contacting affected authorities. For instance, if many cars can be expected on potentially flooded roads this may lead to issuing a higher alert level, as one of the academic experts explained. Some interviewees described attaching probabilities for different scenarios to communicated forecasts. Another forecaster explained that they did not communicate probabilities as emergency managers in this country demanded definitive information. In both cases, however, forecasters communicated their confidence in the forecast in their answers to emergency managers.

National flood forecasters also explained that communication flows continue after the issuing of a warning, keeping emergency managers informed of how the situation develops and supply new forecasts of how long it is expected to go on for.

Decisions and procedures

On the side of EFAS, decisions and procedures for disseminating EFAS information include a schedule forecaster on duty follow, as well as clear criteria for issuing notifications. In addition, there are quality control criteria for these tasks, as well as procedures to handle feedback and determine targets for improvement.

The procedure for issuing notifications is very clearly defined and executed following a schedule. As an EFAS project manager and EFAS forecasters explained, large parts of this process are automatized, like the text of the notification and what emails to send notifications for a particular catchment. Forecasters on duty can add comments but otherwise not modify the notification. Key performance indicators are implemented for the different roles, as for instance exact timing for sending the notifications, to ensure quality and continuity. Additional activities for ensuring quality are to analyse the feedback from the different sources in yearly reports, for targeting potential improvements. In addition, one event is analysed in detail, in a detailed assessment, including targeted feedback collection from partners.

EFAS provides complementary information to national partners. Partners' decisions and procedures included information assessments functions, determining warning levels for forecasting products, preparing dissemination of warnings considering meteorological forecasts or coordinating with meteorologists, disseminating warnings, explaining warning information and triggering response plans.

How these decisions and procedures around using EFAS information are performed varies widely, depending on the performance of their own models and other information sources compared to EFAS and depending on what information they need, or what information they provide to other national institutions.

The entry-point for EFAS information into national decision-making is always through assessments. These assessments are conducted in regular intervals, to determine the current and expected future flooding situation based on a variety of forecasts, including EFAS information, available national models, and other information sources, notably rainfall forecasts. This assessment forms the basis for decisions by flood forecasters in putting together warnings and forecasting products and in some cases, response decisions by emergency managers.

In these assessments, forecasts from different sources are compared, to see if they agree. If they are, this can improve confidence in the prediction. If forecasts disagree, this sets of a search to understand why they disagree. In the case of emergency managers using EFAS, who are often not hydrological experts, this involves contacting the national flood forecasters. For national flood forecasters, who are hydrological experts, decisions are then based on weighing what forecast is more likely to be correct. Next to determining what is behind the different predictions, this involves considering which product tends to perform better.

Decisions are taken based on different information sources, as well as a good knowledge of local conditions, that are cross-evaluated and weighed in the assessments. Several national forecasters explained that forecasting the location of a flood event was often particularly difficult because it depended on where rainfall would ultimately occur. This could result in a situation where there was a high probability for a flood event, but it could potentially occur within a large area. Forecasters in this case, tended to be precautious, rather alerting too many authorities, than too few.

National forecasters explained that they weigh forecasts they consider to be more reliable more strongly in these assessments. National flood forecasters explained that whether the flood forecast was correct was in large parts dependent on the meteorological situation. For this reason, before disseminating warnings, forecasters would also consult meteorological forecasts. Some national forecasters described regular conference calls with meteorological experts to determine their final confidence in the forecast and coordinate how to present warnings to civil protection authorities. In other cases, interviewees described consulting meteorological products, but not necessarily regular calls with meteorologists. In these cases, too, when different forecasts contradict each other, flood forecasters said they would then call meteorological experts, but it was not necessarily a definitive part of the process.

The added value EFAS information can provide to the assessment varies across partners, depending on partners own models and flooding concerns. EFAS information is usually less granular than national flood forecasting models and does not capture all catchments partner organizations are monitoring but focusses on larger catchments. National flood forecasters frequently mentioned monitoring a large number of smaller catchments not included in EFAS. In addition, EFAS often does not have complete information about catchment regulation, like dams or irrigation. It may also not capture specific local flooding concerns, like for instance tidal waves as described by one emergency manager, or ice blockages as suggested by one of the academic experts. Especially, if models rely on similar inputs, like for instance the same rainfall forecast, cross-evaluating EFAS and the local model may not provide much added value. For instance, interviewees explained that EFAS can provide less added value to partners with access to very sophisticated and established flood forecasts, than to countries that have less extensive early warning systems. In transnational river basins, EFAS can provide an overview of what is happening in upstream areas where information may otherwise not have been readily available even to countries with very sophisticated national forecasting systems. EFAS still often provide forecasts for longer lead times than the national model. The uses for EFAS information described by interviewees then ranged from using EFAS in assessments in general, over using it for days further into the future covered by forecasting products or using EFAS as a ‘pre-warning’, in line with what is described in Demeritt et al. (2013, p. 154). Both emergency managers and some national flood forecasters described using pre-warnings to adjust employee-schedules, for instance in case of a flood forecasted to occur during a holiday. Some forecasters also explained a pre-warning would help them to focus their activities in validating their own forecasts. Emergency managers explained that pre-warnings helped smoothen the process of triggering responses.

Based on their assessment, national flood forecasters described determining warning levels, in the form of different traffic light schemes and whether to communicate internal pre-warnings or not. These warning levels are based on what information is communicated in the warning. In some interviews, warning levels were thus explained to be based on hazard information, like water heights or return periods, and in other cases based on impact information.

Translating warning information to responses was realized through linking response plans to warning levels. As several national flood forecasters explained, crisis bodies, taking further response decisions, would convene when a certain warning level was issued based on plans. In addition, response plans for different regions or local authorities outlined specific actions to take in case of a certain warning level. In one case, these plans were in the process of being revised to be based on impact warnings, in another case, the decision to create these plans had been taken only recently. Forecasting agencies dealt with the risk of false alarms by defining accuracy targets and other quality goals for their products, and building awareness for forecast uncertainty among their users, even if they did not communicate probabilities.

Both national flood forecasters and emergency managers highlighted that response decisions ultimately tended to come down to a yes-or-no type decision. This was achieved, in some cases, by the forecasters expressing their confidence in a forecast without communicating probabilities, and in other cases by emergency managers determining response thresholds based on warning probabilities. One emergency manager described conducting own assessments, including national warning products, but also EFAS information and other forecasts to make response decisions.

The higher the lead time of a forecast, the greater the uncertainty associated with the forecast. Interviewees also described different maximum lead times for which warnings were issued, ranging from five days and potentially up to ten days, to three days. In one case where probabilities were not communicated, warnings were issued on shorter lead times against greater certainty. The national flood forecaster, in this case, explained that the civil protection authorities they informed, had a high appetite for receiving more precise information but had a lower appetite for extending lead times and did not want to receive probabilities. In three cases, warnings could be issued for lead times longer than three days, and probabilities were attached to them. Depending on the event, warnings were still often issued for shorter lead times. For instance, for flash flooding, flood forecasters described warnings several hours in advance. In another case, warnings were also issued for three days, but probabilities were communicated with them. Response plans in this case also covered three days, where two days were for planning and preparing responses and the 24-hours before the expected event for deploying resources. Where warnings could be issued for longer lead times, response actions could then also make use of these lead times. Where the emergency manager conducted their own assessment, they were also very flexible in determining whether to trigger response actions or wait and monitor the situation.

Emergency managers explained thresholds for responses depended on weighing costs and benefits. One emergency manager described how expected impacts were weighed against the extent of tolerance, or political will to tolerate false alarms or triggering responses when it would not have been necessary. As one emergency manager explained, response actions could necessitate blocking roads and cancelling events, sandbags and floodgates could lead to complaints by residents. Still, they generally tended toward precaution, because, as one emergency manager at a local authority put it, "*once you're flooded you never want to be flooded ever again"*. One emergency manager explained that they did not consider a forecasted flood event not occurring a false alarm, since these were often situations very close to flooding, they still considered worth reacting to.

4.3 Defining a general frame for the model

Based on the interviews, three different overarching functions that EFAS information was used in were distinguished. The first was the use of EFAS for a forecasting and warning product, with different warning levels implying different planned responses for civil protection authorities receiving the warning. The second was the use of EFAS as a pre-warning, that does not imply operational responses, but is used to target monitoring activities and ensure sufficient human resources. The third was the direct provision of EFAS information, or the indirect provision through warning products EFAS was used to inform, to civil protection authorities to be used for response decisions. From this, the highest aggregation of the reference model was developed. For each of the three main functions, elements were defined, where there are relevant differences between EFAS partners in how EFAS is used or not used in a certain function.

Use of EFAS for forecasting and warning

EFAS aims at providing complementary information to enhance national FEWSs. One of the main functions EFAS is used in then, is for informing national early warnings. Warnings are issued based on a variety of forecast products and additional information that is cross-evaluated and weighed as part of a technical assessment. How much partners rely on EFAS compared to other models used in the assessment differs across partners. Different scenarios for incorporating EFAS in the assessment were distinguished in the model. Warnings are communicated in the form of different types of warning levels associated with a traffic light colour scheme. What information is communicated through these warning levels is another element that differs across EFAS partners. Warnings are prepared relying on meteorological products, with the relationship and coordination between hydrological and meteorological forecasters differing across EFAS partners. Finally, warnings are disseminated to authorities and the public. How this dissemination process is organized and what additional information or supporting communication is involved also differs across partners.

Use of EFAS as a pre-warning

EFAS provides medium-range flood forecasts, of up to 15 days into the future. National early warnings and response plans have to cover a wide range of events and operate on shorter timescales, from five days to a day. Depending on the event, partners may need to react just several hours in advance. EFAS can thus sometimes give partners an indication of events exceeding the timescales of their warning products and response plans. This information is assessed and weighed against other information sources as well and again, differently across EFAS partners. How pre-warning information is disseminated also distinguishes EFAS partners.

Use of EFAS for response

Responses to flood warnings are based on emergency plans that connect to the warning levels. Different plans and responses are triggered depending on the warning level. How response plans are activated, and initial decisions taken differs across partners.

Designing the reference model frame

The model was designed using instantiation. Process fragments were designed from the interviews in the first iteration. Following that, a general model was constructed, containing placeholders describing functions for which different instantiations exist. Subsequently, each different instantiation was modelled. In the following section, general functions and the existing instantiations are outlined. They are visualized in **Fehler! Verweisquelle konnte nicht gefunden werden.**. The following section outlines the elements where different configurations across partners exist, within each of the three overarching functions.

Within the use of EFAS for forecasting and warning, EFAS partners perform an assessment where different information sources are considered and weighed against one another to inform a warning product. This assessment can either 1) rely on national models, 2) include EFAS for certain predetermined days into the future, that a warning product is issued for or, 3) generally include any EFAS information available.

The next element is how warning levels are determined. Warning levels can either be based on 1) hydrometeorological information without probability information, 2) hydrometeorological information including probabilistic information, 3) expected impacts and associated probabilities based on an impact-model or, 4) expected impacts and associated probabilities based on a model and consultation of local civil protection authorities.

The next element is to prepare forecasts and warnings for dissemination, by assessing meteorological information and flood forecasts to determine final confidence in the forecast. This can either be done 1) by directly contacting a meteorological agency or department, or 2) by assessing flood forecasts against meteorological forecasts without directly talking to a meteorologist.

Within the use of EFAS as a pre-warning, information exceeding the lead time at which warning products are disseminated is received either by a forecasting agency or by a civil protection authority. This information is also evaluated through an assessment. It can either 1) be included in an assessment for dedicated forecasting products covering medium- to long ranges or an add-on to the warning product, 2) be assessed by a flood forecaster to determine whether significant events are expected beyond the warning products lead time, or 3) be assessed directly by an emergency manager who then decides to adjust employee schedules or not.

Pre-warning information is also prepared for dissemination by assessing it against meteorological forecasts. This occurs in a similar fashion to the warning and forecasting process, where either, forecasters directly contact meteorologists or cross-evaluate their forecasts using meteorological forecasts.

Pre-warning information may then be 1) disseminated in the form of a medium- to long-range forecast product or as an add-on to the warning product, via email and websites 2) be disseminated verbally during regular calls with civil protection authorities. Pre-warning information may then be acted on to ensure sufficient human resources will be available, to focus monitoring activities or to schedule meetings.

For disseminating forecasts and warnings, first warnings are sent out. In one scenario, 1) warning information is disseminated simultaneously directly to the public via a webpage as well as to affected authorities, via emails and the webpage. In another scenario 2) warnings are disseminated only by emails to affected authorities and only disseminated to the public later.

Forecasters then provide guidance on the warnings. In one scenario, 1) guidance is provided passively by forecasters, upon receiving a phone call about a warning. In a second scenario, 2) guidance is provided actively in regular calls with civil protection and by actively calling affected authorities if they are not included in those calls.

Within the use of EFAS for response, response plans are activated corresponding to the warning level issued.

In one scenario, 1) response plans are activated, and a forecasting agency contacted for decision-support and new information as the situation develops. In a second scenario, 2) response plans are activated, and new information monitored while the forecasting agency can be contacted for interpretation support. In a third scenario, 3) civil protection authorities conduct their own assessment, including national warnings and can decide to contact the forecasting agency for interpretation support, activate response plans and take additional steps, or not to activate plans and continue monitoring the situation. Activating response plans also involves issuing warnings to the public in affected areas containing instructions on how to react.

4.4 Demonstration of the model

In the following paragraphs, it is demonstrated that the model adequately fulfils the Design Objectives that were created and is applied exemplary to a problem identified in the literature review. Generalizations made for any of the objectives are highlighted, justified, and considered in the demonstration of the model. To apply the model to a particular organization, the instantiations best fitting this organization should be selected. Following that, missing aspects should be added through further specialization or instantiation. For instance, the general roles can be specified into the exact roles and organisations performing a given function. Additional information used can be specified. The model should help evaluating current use of EFAS, by situating current use, highlighting alternatives and aspects to consider when introducing EFAS, or adapting current use of the system. The demonstration outlines which aspects are not included in the model and need to be considered when applying it.

Roles and responsibilities

The objectives to depict communication and decision responsibilities are fulfilled by depicting in abstract the roles involved and linking them to all communication and decision functions shown in the model. For targeted supporting communication, both the disseminating role and the receiving role were modelled, to always highlight all roles involved. The roles depicted in the model are national flood forecasters, emergency managers and meteorologists. National flood forecasters are the recipients of EFAS information in national hydrometeorological services, who prepare and communicate national flood forecasts and warnings. Meteorologists refer to their equivalent for meteorological forecasts and warnings. The relationship between meteorological agencies and hydrological or hydrometeorological agencies differs between countries. This was abstracted away in the model. The model only specifies communication between flood forecasters and meteorologists. Emergency managers refers to people who carry out responsibilities for activating emergency response plans and carrying out flood response activities. The countries, which the model is based on differ in size and the way in which administrative units are defined. To preserve clarity, the level at which national flood forecasters, emergency managers or meteorologists work, like national, regional, or local authorities, was abstracted away in the model.

One problem identified in the literature that can occur in early warning systems was unclear communication or decision responsibilities (Perera et al. 2020, p. 4; Sukhwani et al. 2019, p. 7). Flood forecasters and emergency managers clearly described EFAS users in their organizations. Arrangements to ensure training for these users were often not or less clear, however. Especially if EFAS notifications are rarely received, this may lead to a lack of routine among EFAS users. They may also be unfamiliar with new information included in EFAS. Identifying recipients of EFAS information could aid in finding a strategy for regular user training. This could for instance include incorporating the interpretation of EFAs information in drills, organizing trainings internally, or coordinating one EFAS training with the dissemination centre across multiple smaller organizations. EFAS could consider proposing trainings to new users proactively.

This can be applied to the pre-warning function. As one academic expert explained, pre-warnings often had no formal status. However, they were described as useful in every interview with flood forecasters and emergency managers. If pre-warnings can be issued frequently, EFAS partners can consider moving from providing verbal pre-warnings during regular calls with a more limited circle of decision-makers to using EFAS information and other available medium-range forecasts to provide a forecasting product for this function. This can then be disseminated alongside other forecasts to a wider range of decision-makers, establishing routines around using such pre-warnings. It could help ensure pre-warnings can be capitalized on, helping emergency managers make resourcing decisions for busy periods, or ask clarification questions and get an idea of what to expect earlier on. Forecasting agencies can reconsider this, with improvements of EFAS adding more catchments.

Communication Flows

The objective to depict communication channels, as well as advice and supporting communication was achieved by creating a function describing each communication channel. The communication channels identified were for example the EFAS platform itself, emails, or phone calls. Phone calls can also be conducted as video conferences, which is not differentiated in the model. For each communication channel, the model highlights whether it is mandatory or optional. The dissemination channels to the public also differ but are abstracted away in the model as it focusses on dissemination between authorities. These dissemination channels can include websites, apps, sign-up services, location-based alerting systems, sirens or also community members going from door to door. A more thorough discussion of different warning dissemination systems to the public is contained in Bopp et al. (2021).

The objective to depict what information is being communicated was achieved by linking each communication-function with the information or communicated through it. The information identified were for example flood forecasts and warnings, meteorological forecasts and warnings, or forecasters' confidence in a forecast. Each information element is explained in detail in the process description for the general function it is relevant for. For the assessment functions, situational information that can be included was abstracted through an object labelled "additional information".

Perera et al. (2020, p. 4), notes issues in capitalizing on early warnings can result from weak working relationships between forecasting agencies and forecast users resulting in coordination issues. For instance, one flood forecaster mentioned issues where emergency managers may not follow up on warning information that was unclear to them. At the same time, the forecasting agency may be overwhelmed with phone calls, if too many authorities call for guidance shortly after a warning is issued. In these cases, EFAS partners may consider moving toward providing guidance proactively in a conference call to authorities that warnings were issued to. To ensure clarity in presenting warnings, EFAS partners can consider coordinating the presentation of warnings between meteorological and hydrological warnings more closely by adopting direct exchange between hydrologists and meteorologists before issuing warnings. In addition, flood forecasting agencies and civil protection agencies could consider moving toward giving the flood forecasting agency a more proactive role in response decisions, providing interpretation or decision-support. This type of decision would of course need to be discussed and taken jointly by forecasting agencies and civil protection authorities, considering additional trainings, employees needed and timing aspects of these communication activities.

Decisions and Procedures

The objective to depict decision-options for using EFAS information was fulfilled by modelling a function for each decision where EFAS information can feed in directly, or indirectly through products where it fed into. The modelled decision-functions all centre around assessing a variety of information sources and coming to a decision. The objective to depict what information is being used was achieved by modelling the information used or created as part of each decision-function. This includes information inputs, like EFAS information, or forecasting agency's own models, or information outputs, like whether warnings communicate different scenarios and their probabilities, or the most likely scenario without displaying probabilities.

Forecasting agencies continuously update and re-evaluate their forecasting products and inputs into these. This can involve feedback from forecast users and also includes forecast verification. As outlined above, to keep the scope the article manageable, these feedback processes, as well as partners' feedback to EFAS were not included in the model. The model addresses operational use of information. The model also includes emergency plans containing thresholds and guidelines on issuing warnings. How these plans are created, thresholds are set, and guidelines are created is not depicted in the model.

Depending on whether they rely on hazard or impact-based warnings, EFAS partners could re-evaluate which EFAS layers they use. In several interviews, forecasters described moving toward impact warnings, because of demand for this type of information by emergency managers. One emergency manager explained they were in the process of creating emergency-plans based on impact information. At the same time, the impact assessment layer included in EFAS was often not used in assessments, or not known by interviewees. If warnings are issued based on impact assessments, EFAS partners can consider utilizing the impact layer in their assessments and re-evaluating its use as EFAS improves.

4.5 Evaluation of the model

For evaluation, four follow-up semi-structured interviews were conducted between May 5th and May 10th. Two of these interviews were conducted with interviewees from national forecasting agencies, one interview was conducted with an interviewee from an EFAS centre, and one interview was conducted with an academic expert. As discussion-basis for the interview, the entire model was presented at the start of the interview by the interviewer. Interviewees were asked whether the model was clear and accurate, and any suggested changes were discussed. In addition, follow-up questions for analysing and discussing the model were asked.

Interviewees all agreed that the model was clear. The interviewed national forecasters agreed that the model covered how the described functions were performed for their case. Following the consensus approach to truth adopted by this thesis, the model can therefore be considered successful. The limited number of interviews and general limitations of semi-structured interviewing of course remain a limitation of the paper. Changes suggested during evaluation interviews, were implemented following the interview and included in the next evaluation interview. The final model was then sent to interviewees for comments.

After the model had been finalized, two additional interviews with new interview partners, one additional national forecaster and one emergency manager were conducted. Based on the interviews, no changes were made to the model, but discussion factors, like communication flows across several institutional levels, or ongoing changes to the early warning system examined. The national forecaster agreed that the model was clear and highlighted that the creation of detailed emergency plans linked to warnings, in this case, had only recently begun. In addition, the forecasting agency was in the process of establishing models to forecast expected impacts to decision-makers. In case of flood events, the civil protection agency was acting in a coordinating role, summarizing, and distributing situation assessments to other civil protection agencies, who used these assessments for their own decisions and assessments. The emergency manager could not comment on whether the model covered procedures of other civil protection and forecasting agencies for this case. The interview was useful to highlight how functions within nearly warning systems, in this case an assessment function by emergency managers, may be performed across several institutional levels and organizations.

The following section summarizes changes that were made to the model resulting from the evaluation. These were to further differentiate between the warning product made available to the public and the one available to civil protection. Warnings to the public may be issued at two stages, in some cases the forecasting agency disseminated forecast information publicly when it’s forecast products are ready. This can be the same information that is provided to civil protection authorities, however it may also be different information, for instance more general or issued on shorter lead times. This was distinguished from warnings sent out when a flood event is considered imminent, containing instructions, for instance to vacate certain areas. These warnings were disseminated as part of the emergency response, and thus at a later point than when the forecasts were issued to civil protection agencies before a flood event. In addition, the information objects reflecting whether probabilities were communicated or not, were rephrased to show that probabilities are used to reflect different potential scenarios. Response plans and forecaster’s confidence in their forecast were added as information. The preparation function, during which meteorological forecasts are consulted or the meteorological department contacted, had originally only been included in the forecasting and warning process. It was also added to the pre-warning process during evaluation. Communication flows were highlighted more clearly in the model, by always assigning both involved roles to respective functions.

In the following section, the final model, including changes made during evaluation is presented.

4.6 Describing the Reference Model

The following section will describe the reference model for the use of EFAS for forecasting and warning. The highest level of aggregation depicted in the reference model (**Fehler! Verweisquelle konnte nicht gefunden werden.**) shows EFAS feeding into three general functions that are performed on the national level. These are the use of EFAS for forecasting and warning products, the use of EFAS as pre-warning information and the use of EFAS to trigger and inform emergency response. Forecast dissemination was modelled as a separate function that can be used in both the pre-warning and forecasting and warning process.

Partners generally access EFAS following two scenarios. Either a partner logs in to the EFAS web platform upon receiving a formal or informal EFAS notification, or an EFAS flash flood notification. Partners can also display the EFAS web layers within their own systems. Alternatively, partners actively monitor EFAS, by logging on and checking the EFAS flood and flash flood layers in intervals they set themselves. These intervals could range from checking EFAS daily to weekly but depend on the partner and the time period. Different partners receive varying amounts of EFAS notifications, depending on how often a forecasted event fulfils notification criteria. Partners may log in to the platform more regularly in a period where they expect more flood events. For instance, during rainy months partners may check EFAS more frequently. Similarly, once a notification has been received and an EFAS partners decides to monitor it, they will log in to the EFAS platform more frequently to see how the notification evolves and how persistent it is.

In the following sections, the three functions will be explained in detail. First, a general skeleton of each function is described. Within this process, there are some functions that are performed differently by EFAS partners, as described above, and visualized in Figure 5. For each of the elements described in the table, an instantiation was modelled. Each instantiation is explained in detail and situated in the general process.

4.6.1 EFAS for forecasting and warning products

Partners can use EFAS to feed into their forecasting and warning products if the platform is forecasting a flood event within the lead time of the warning product (**Fehler! Verweisquelle konnte nicht gefunden werden.**). These lead times ranged from three to five days across organizations contacted for this article.

Upon receiving a notification for a flood event, or when they scheduled logging in to EFAS, partners conduct an assessment in which different flood forecasts are cross-evaluated and weighed against one-another in conjunction with other information sources. This way forecasters improve their understanding of whether or not to expect floods based on available information. The information included in the assessment and how it is included varies across EFAS partners. The assessment function is the first function for which different instantiations exist across EFAS partners in the forecasting and warning process.

Once EFAS partners conclude their assessment, they convert this information into warning levels which the warning product communicates. Warning levels are depicted as a colour scheme expressing the expected severity of a flood event, where green indicates no danger and red, or purple indicate extreme severities. Warning levels can communicate different types of information and are either based on expected discharge, expressed through return periods or water heights, or based on expected impacts expressed as likely flooded areas and expected damages. Another distinguishing factor is whether partners communicate probabilities or not. This is for instance done by communicating several scenarios in the warning and attaching probabilities to them. Determining the warning levels is the second function for which different instantiations exist for EFAS partners in the forecasting and warning process.

Once the warning level is determined, partners prepare forecasts and warnings for dissemination, determining their confidence in the forecasts. Confidence in their forecast is among the main information flood forecasters communicate to civil protection authorities. Confidence depends on agreement between the different flood forecasts included in the assessment function, whether they match up with meteorological forecasts, probabilities for different outcomes in those models (e.g. number of ensemble members agreeing) and the persistence of forecasts over time. Confidence in the flood forecasts used as inputs for the assessment also depends on their performance metrics and their historical performance. Meteorological forecasts are crucial to assess and understand flood forecasts. As such, they play an important role in determining how confident flood forecasters are in their forecasts. How meteorological forecasts are incorporated in this process varies across partners and is the third function for which different instantiations exist for EFAS partners in the forecasting and warning process. Meteorological forecasts are also always included during the assessment function.

Once warning and forecasts are ready for dissemination, they are disseminated through a warning dissemination process that is described separately as mentioned above. In the reference model, this is represented through a process interface. The forecasting and warning disseminating process (**Fehler! Verweisquelle konnte nicht gefunden werden.**) is described in detail in a dedicated section.

After the dissemination is concluded, partners continue monitoring and providing information updates. They may check the EFAS platform in regular intervals or at a later point, upon receiving a notification again for a new flood event. If partners received an EFAS notification, they may monitor the notification more frequently to see how the forecast evolves.

In the next paragraphs, the instantiations for the assessment functioning, the function for determining the warning levels and the function for preparing for dissemination are described.

For the assessment function the reference model distinguishes three different instantiations. The first variant (**Fehler! Verweisquelle konnte nicht gefunden werden.**) sees partners including EFAS information in the assessment for some defined days covered by their warning product. For example, EFAS information could be included for lead times exceeding two days in the warning product. In this case, national flood forecasters would log onto the EFAS web platform and cross-evaluate and compare flood events forecasted by EFAS with other models and additional information. This includes forecasts based on a partner’s own flood forecasting models, and other information depending on local conditions, like for instance, information on soil moisture, snowmelt or tidal waves. Meteorological information is also included here, in the form of precipitation forecasts. These are also used as inputs for the forecasts itself. This information is thus useful when comparing forecasts, to understand what is causing certain outputs. For instance, different flood forecasts may disagree because they are using different input values for soil moisture or expected precipitation. As explained earlier, this is abstracted away under the label “additional information”.

In a second instantiation (**Fehler! Verweisquelle konnte nicht gefunden werden.**), partners generally include EFAS for each day covered by their warning product and again, cross-evaluate it in conjunction with a range of other information sources. So, for example, rather than only including EFAS in their assessment for the third day in the future, they also include it for the second and first day.

In a third instantiation (**Fehler! Verweisquelle konnte nicht gefunden werden.**), EFAS partners do not include EFAS in the assessment for their warning product. In this case, partners rely on their own models, rainfall forecasts and additional information. This scenario may be adopted because a partner needs to issue warnings at a high level of certainty and is not sufficiently confident in EFAS information to include it in the assessment. The national model is better calibrated for the area a partner is monitoring, including all relevant catchments and information on catchment regulations. In this case, partners may still use EFAS information to focus their attention on evaluating their own forecasts but will not rely on EFAS for their assessments.

While the assessment function describes how partners cross-evaluate information used as inputs for their warning product, the function for determining warning levels describes what information outputs these are translated into. Warning levels represent thresholds and can communicate different information. In a first instantiation (**Fehler! Verweisquelle konnte nicht gefunden werden.**), partners may communicate discharge warning levels, for example based on flood return periods assigned to expected water heights without attaching probabilities. In this case, the warning product would be communicating the peak threshold exceedance, the location in the river where the exceedance is expected to occur, as well as expected peak timing and duration of the flood event. The levels communicated in this case are based on the flood forecasters best guess based on the outcome of the assessment procedure. The best guess describes the values that the forecaster is most confident in to issue warnings with a better degree of certainty. In addition, warnings are always issued based on guidelines, determining for example what return period constitutes a yellow or red warning, or at what lead times a red warning may be issued.

In a second instantiation (**Fehler! Verweisquelle konnte nicht gefunden werden.**), warning levels are again based on discharge levels, but probabilities are expressed in the warning. In this case, aside from communicating a best estimate scenario, the warning may also include a reasonable worst-case scenario.

In a third instantiation (**Fehler! Verweisquelle konnte nicht gefunden werden.**), forecasting agencies communicate expected impacts of flood events. In this case, forecasted discharge values are postprocessed into an impact model simulating which areas will be flooded. Because this is computationally very demanding, as one interviewee noted, it is not calculated in real-time. Rather, the impact model is based on flood risk maps, that can be created from historical data or calculations that were done beforehand. Based on which areas are expected to be flooded, and data on population and land use, the model will estimate expected damages. The EFAS platform also provides an information layer displaying expected impacts. This impact information is translated into warning levels for the likely flooded areas, as well as attached probabilities. Flood forecasters again determine a best guess and reasonable worst-case scenario. Expected peak timing, and duration are also included.

In the fourth instantiation (**Fehler! Verweisquelle konnte nicht gefunden werden.**), flood forecasters determine impact warning levels not only based on model output. In addition to the model outputs, local civil protection authorities are consulted in phone calls to finalize impact warning levels. Since impact models of course also provide estimates, this way confidence in the warning level can be improved by incorporating knowledge of local conditions.

In the function to prepare forecasts for dissemination, flood forecasters determine their final confidence in the forecast by consulting meteorological forecasts. The first instantiation (**Fehler! Verweisquelle konnte nicht gefunden werden.**) sees flood forecasters directly contacting meteorologists, either by calling a separate meteorological agency, or a meteorological department within the hydrometeorological service. Flood forecasters and meteorologists cross- evaluate flood forecasts and meteorological forecasts to determine how confident they can be in their flood warnings and forecasts. Based on these discussions, flood forecasters potentially adjust how they communicate forecasts and expected scenarios to emergency managers. In an alternative instantiation (**Fehler! Verweisquelle konnte nicht gefunden werden.**), flood forecasters would not directly contact meteorologists, but still cross-evaluate their flood forecasts and warnings using meteorological forecasts.

4.6.2 EFAS for pre-warning

EFAS partners also use EFAS as pre-warning information. If EFAS is forecasting flood events with lead times exceeding the national warning product’s lead time, this information is used as a pre-warning (**Fehler! Verweisquelle konnte nicht gefunden werden.**).

In a first step, EFAS partners assess and cross-evaluate the pre-warning information in conjunction with other information sources. The assessment is the first function for which instantiations exist in the pre-warning process. Once the assessment is concluded, pre-warning information is prepared for dissemination, which is the second function for which instantiations exist within the pre-warning process. Following that, the pre-warning information can be disseminated, which is the third function for which instantiations exist in the pre-warning process. The dissemination concludes the prewarning process. Partners then go back to monitoring, regularly checking on the evolution of events forecasted in the pre-warning information.

For the assessment of pre-warning information, there are three instantiations. In the first instantiation (**Fehler! Verweisquelle konnte nicht gefunden werden.**), the forecasting agency has dedicated products for longer lead times and its own medium-range forecasts. In this case, the EFAS information feeds into the assessment for these products, together with national flood forecasts covering longer lead times, rainfall forecasts and additional information.

In the second instantiation (**Fehler! Verweisquelle konnte nicht gefunden werden.**), partners do not have national medium-range forecasts and no dedicated medium-range forecasting products. In this case, flood forecasters assess the EFAS information together with rainfall forecasts and additional information to determine how confident they are in the pre-warning. If the flood forecaster concludes that there is a significant risk of flooding, they prepare this pre-warning information for dissemination. If the flood forecaster is not confident that there is a significant risk of flooding, they do not disseminate a pre-warning. The forecaster then monitors the evolution of the forecast and regularly logs back in to EFAS. In this case, the dissemination step in the pre-warning process is skipped.

In the third instantiation (**Fehler! Verweisquelle konnte nicht gefunden werden.**), rather than only receiving pre-warning information that has been interpreted by a flood forecaster, civil protection authorities have direct access to EFAS and conduct their own assessment. In this case, pre-warning information is assessed by an emergency manager, including EFAS information, national flood forecasts, rainfall forecasts and additional information. If the emergency manager concludes that there is a significant risk of flooding, they check and potentially adjust the employee schedule to make sure that enough employees are available to respond to a flood event. If the emergency manager concludes that there is no significant risk, they keep monitoring the evolution of the flood forecasts regularly. In this case, the dissemination step in the pre-warning process does not take place as the emergency manager is the end-user of the pre-warning information. The emergency manager can however receive national pre-warning information from national flood forecasters that is also used in the assessment.

The function for preparing pre-warning information for dissemination is similar to the function for preparing warning information for dissemination. Again, in one instantiation (**Fehler! Verweisquelle konnte nicht gefunden werden.**), flood forecasters talk directly to meteorologists to determine their confidence in the pre-warning information. In a second instantiation (**Fehler! Verweisquelle konnte nicht gefunden werden.**), they check meteorological forecasts to determine their confidence in the flood forecast, without directly contacting a meteorologist.

For the dissemination function, two instantiations exist. If there are dedicated forecast products for medium- to long ranges, they are disseminated through the normal dissemination procedure that warning forecasts are also disseminated through (**Fehler! Verweisquelle konnte nicht gefunden werden.**). Pre-warning information is then used by both forecasting agencies and civil protection authorities to adjust their schedules to make sure that enough employees are available in case significant flood events are expected.

If there are no dedicated forecast products to disseminate pre-warning information through, it is disseminated during regular calls between flood forecasters and emergency managers (**Fehler! Verweisquelle konnte nicht gefunden werden.**). Flood forecasters explain the pre-warning information, their confidence in it, and that a warning is likely to be issued. Both flood forecasters and emergency managers then check and potentially adjust schedules to make sure enough employees are available to handle the expected flood event.

4.6.3 Warning and forecast dissemination

The following paragraphs outline the forecast and warning dissemination process (**Fehler! Verweisquelle konnte nicht gefunden werden.**).

The forecasts and warning dissemination process begins if either a warning forecast or pre-warning forecast is ready for dissemination. Warnings and forecasts are first sent out, which is the first function for which instantiations exist in the dissemination process. Once they are sent out, forecasting agencies provide guidance on the forecasts and warnings to recipients, which is the second function for which instantiations exist in the dissemination process. Following that the dissemination process is concluded.

For sending out forecasts and warnings, two instantiations are distinguished in the model. In the first instantiation (**Fehler! Verweisquelle konnte nicht gefunden werden.**), flood forecasters disseminate forecasts and warnings by email to emergency managers. They also disseminate forecasts and warnings to the public, typically through a webpage. It should be noted, that next to these early warnings to the public, shorter term warnings are also disseminated to the public by emergency managers as part of emergency response. These warnings contain for instance instructions on how to react or which areas to stay out of, and are disseminated, for instance through location-based SMS, emails or going from door to door. This function will be explained in brief as part of the emergency response process.

In the second instantiation (**Fehler! Verweisquelle konnte nicht gefunden werden.**), flood forecasters do not disseminate warnings directly to the public, but only by email to civil protection authorities. Warnings to the public in this case are in general issued at a later stage.

For the function to provide guidance about warnings, there are three different instantiations. In the first instantiation (**Fehler! Verweisquelle konnte nicht gefunden werden.**), guidance is provided passively, if it is requested. In this case, if flood forecasters receive a call, for instance from civil protection authorities or the press, they will explain warnings and forecasts and their confidence in them and make sure the caller is correctly interpreting the forecast. Of course, the forecasting agency can only receive calls on warnings from the public or the press, once warnings have been issued publicly.

In the second instantiation (**Fehler! Verweisquelle konnte nicht gefunden werden.**), emergency managers are provided guidance on warnings and forecasts during regular calls with flood forecasters. Further calls are scheduled with affected civil protection authorities not included in the regular calls. For example, regular calls can include civil protection authorities on the national level. Further calls are then scheduled with local civil protection authorities who were issued flood warnings. Guidance is then provided passively to callers from the wider public once warnings are issued to the public.

4.6.4 EFAS for emergency response

In the following paragraphs, the process of triggering emergency response on the national level based on warnings is outlined (**Fehler! Verweisquelle konnte nicht gefunden werden.**). Once civil protection authorities receive a warning from the forecasting agency, emergency plans corresponding to the warning level are activated. Plans involve bringing together decision-making bodies like crisis committees, which take further flood management decisions. Plans for instance lay out the roles and communication flows between different actors within these decision-making bodies. Forecasting agencies can also have roles within these plans, but this depends on the EFAS partner and the scale of the flood event. They also lay out what actions should be taken at what warning level and how the plan is escalated or de-escalated to another level. Timescales for activating emergency plans ranged from three to five days, parallel to warning lead times. The first days prior to a flood event may be used to move people and equipment to the right places and start broadcasting warning information to the public. Aside from information about the expected flood, this also includes information about the response, for instance certain roads being blocked. Response actions then tend to start in the 24 hours preceding an expected flood event. Of course, for warnings issued on shorter lead times, the response needs to operate on shorter timescales as well. This is the first function for which instantiations exist in the emergency response process. Once the emergency response plans are activated, civil protection authorities manage the flood event and keep receiving information updates from forecasting agencies, who may check the EFAS platform again. Eventually, the flood event ends, concluding the response process.

In the function for triggering emergency response plans, three instantiations exist. In the first instantiation (**Fehler! Verweisquelle konnte nicht gefunden werden.**), emergency managers receive a warning and emergency plans corresponding to the warning level are activated. In this scenario, emergency managers then contact flood forecasters, who based on their confidence in the warning give them decision support. Emergency managers receive national warning information and activate response plans. Next, they contact the forecasting agency for decision support and the forecasting agency outlines their confidence in any information they pass on to emergency managers and offer decision-support. While decisions are still ultimately taken by emergency managers, they are discussed with flood forecasters in this instantiation. Decision-support in this case does not mean discussing specific actions, but rather relates to initiating decisions, like activating plans or beginning to move equipment. Emergency managers now take decisions to issue shorter term warnings to the public in affected areas, as mentioned earlier. These warnings including instructions on how to react, like for instance vacating and staying out of certain areas. Emergency managers make sure all affected citizens, as well as relevant and interested organizations receive these warnings. For instance, tourism organizations or sports venues may make arrangements to also receive warning emails and call events off.

In the second instantiation (**Fehler! Verweisquelle konnte nicht gefunden werden.**), civil protection authorities receive warnings, and again, activate corresponding emergency plans. In this case, contacting flood forecasters is optional for emergency managers. Emergency managers contact flood forecasters if they want to receive further guidance on warnings. In this instantiation, flood forecasters strictly provide interpretation support based on their understanding of and confidence in the forecast. Emergency managers do not ask for decision-support, but make sure their understanding of the forecast is correct. In both cases, whether they contacted the forecasting agency or not, emergency managers then disseminate warnings to the public in affected areas similar to the first instantiation.

In the third instantiation (**Fehler! Verweisquelle konnte nicht gefunden werden.**), civil protection authorities have direct access to EFAS. An emergency manager assesses and cross-evaluates national warning information, EFAS information, rainfall forecasts and additional information, which can also include local models. When the assessment is concluded, the emergency manager can decide to contact the forecasting agency for interpretation support or decide to go ahead without contacting flood forecasters. The emergency manager then decides whether to active emergency response plans, or to wait and monitor how forecasts evolve and reconsider at a later point in time. If the emergency manager decides to activate emergency response plans corresponding to warning levels, they also issue warnings to the public in affected areas, similar to the other instantiations. This instantiation was modelled after response on the local level in some countries, giving local emergency managers more leeway in determining how to respond to an expected flood event.

4.6.5 Additional remarks

Which instantiation fits a particular organization can differ across organizations within the same country. For example, response at local levels may be organized largely independently, while for events exceeding a certain scale, regional or national authorities organize the response and forecasting agencies are more directly involved. The model only depicts instantiations based on interviews with EFAS partner organizations. It is possible that the third instantiation, where emergency managers conduct an assessment to determine whether to activate response plans or not, exists in cases where the emergency manager does not have access to EFAS. It was, however, not covered in the interviews conducted for this thesis. At the same time, it is worth noting, that even if emergency managers have access to EFAS, given that EFAS does not cover all catchments, not all assessments include EFAS information.

How warning information is disseminated to the public differs and is abstracted in this model. This model makes a differentiation between warning information at two different points in the early warning process, one by the forecasting agency, in parallel to warning dissemination to authorities, and another one by emergency managers in the lead-up to further emergency responses, potentially involving the forecasting agency. Depending on how exactly warnings are disseminated, there could be even more organizations involved, for instance a separate authority offering a warning dissemination service. Warning dissemination may even differ across organizations within the same country.

5 Discussion

In this section, the model's key implications are discussed, and recommendations formulated. Following that, limitations are outlined.

This article set out to propose a reference model for communicating EFAS alerts in national early warning systems to overcome barriers to their use for decision-making. The designed model, highlights three purposes EFAS is used in in national early warning systems, issuing warnings and forecasts, issuing pre-warnings and triggering emergency responses. The model depicts general functions in which EFAS information can be utilized for these three purposes. It depicts alternatives across EFAS partners of how EFAS information impacts decisions and moves through the early warning system. The model has implications for evaluating the use of EFAS information. The model depicts different alternatives for utilizing EFAS in assessments, organizing communication flows and linking warnings to response decisions. As EFAS is continuously improving, partners should reconsider their use of the system. The following section outlines relevant factors for re-evaluating uses of EFAS that were discussed during interviews and highlights challenges. The section discusses confidence in forecasts, training and experience of forecast users, coordination between forecasters and emergency managers, implementing change projects and forecast verification, partners' feedback to EFAS, communication flows and timing, the SOV principle and third-party partners as well as the availability of plans and connection to the wider FRG context

Confidence in forecasts

EFAS information generally entered national early warning systems through an assessment function, alongside other information sources. The assessment was in most cases conducted by national flood forecasters, and in some cases by emergency managers. The impact of different information sources on the assessment depended on how confident flood forecasters and emergency managers were in their different information sources. The importance of confidence in forecasts was highlighted by a flood forecaster and could be described as the currency with which decisions are taken in the FEWS. This includes confidence by forecasters in different information sources and the forecast they ultimately disseminate, but it also includes the confidence of their user groups in the forecasts they receive.

Forecasters thus are concerned with building confidence in their forecasts among forecast users, and EFAS faces the same challenge. The main reasons for not using or relying less on EFAS in an assessment were EFAS users being more confident in national forecast models, EFAS not including many smaller catchments and EFAS users lacking experience with the system because they rarely received alerts. EFAS was relied on more strongly, where forecasters and emergency managers where more confident in it, where EFAS alerts were received very frequently and in cases where there were no, or less extensive national flood forecasts.

Confidence in national forecasts was usually higher than in EFAS, as national forecasting systems were better calibrated and included more catchments, information on catchment regulation as well as finetuned thresholds. When asked about potential improvements to EFAS, forecasters and emergency managers mentioned a more granular model, including smaller catchments, running the model more frequently, improving the precision of model inputs, like soil moisture or precipitation, extending lead times, and including more information on catchment regulation. EFAS is improving these aspects across contract periods. Therefore, partners should re-evaluate their use of EFAS, when the system is updated. One forecaster suggested designing algorithms for postprocessing EFAS information, received through webservices and converting it to equivalent national thresholds.

Training and experience of forecast users

Flood forecasters based their confidence in a flood forecast in their expertise in interpreting and cross-evaluating different models and information about model performance. If models agreed and forecasts were persistent, forecasters were more confident in their forecast and communicated this to forecast users. Interpreting meteorological information and coordination with meteorologists was then also an important basis for confidence in the flood forecast. Flood forecasters described forecast users as a very heterogenous group in terms of their experience in interpreting forecasts, as well as their confidence in and responsiveness to warnings. Aside from experiences with forecasting, this also depended on other operational demands on these organization's resources and their priorities, for instance, fire brigades were described as more responsive than police or local authorities. Emergency managers then based their confidence in the expertise of the flood forecasters, the performance of the warnings and trust in the source of information. So, while a flood forecaster explained that they do not use EFAS to issue earlier warnings, as they cannot neglect their own models based on EFAS information, an emergency manager highlighted that they saw no reason not to use EFAS information, as it was official information from the European Union and had proven reliable to them. One emergency manager highlighted the importance of training, due to the complexity of the interface and the amount of information. Training may be even more relevant where receiving EFAS notifications is not a routine occurrence. In cases where EFAS partners received EFAS notifications very frequently, or there were less national flood forecasting capabilities, EFAS information was monitored more routinely. These routine users were experienced users who were confident in using EFAS information. Where EFAS only rarely forecasted floods, problems as simple as a forgotten password could complicate its use.

Coordination between forecasters and emergency managers

Across interviews, there were slight differences in how forecasters and emergency managers viewed their roles. One difference related to the balance between precision and precaution. Forecasters invested a lot of effort into giving accurate forecasts and wanted to avoid issuing false alarms. If a decision can be postponed, forecasters thus sometimes prefer to wait, while emergency managers prefer acting earlier and doing too much over doing too little. This is in line with how Demeritt et al. (2013, p. 154) describe the tension between issuing earlier warnings and issuing precise warnings faced by flood forecasters. Ultimately, forecasters also favoured precaution. For instance, when faced with uncertainty around the location of a flood event, two forecasters explained that in this case they would issue warnings to all authorities which may be affected.

While emergency managers generally described that reacting to a warning tended to come down to a yes-or-no question, their needs from the forecasting agency differed. In one interview, the emergency manager was a forecasting expert themselves, and thus had less need for interpretation support by the forecasting agency. The two other interviewed emergency managers were crisis management experts who did rely on interpretation support from a forecasting agency. They also highlighted the forecasting agency's role in aiding them in utilizing EFAS information.

Implementing change projects

These different views on responsibility distribution between forecasting agencies and civil protection authorities were also visible with regards to implementing changes. Similar to how EFAS is implementing projects to improve their service, national forecasting agencies also conduct such project work. And like EFAS is collecting feedback about model performance and partner's demands, national forecasting agencies verify their products and try to meet the information needs of their user groups. The involvement of civil protection agencies in improvement projects and the access of forecasting agencies to feedback and reports then differed across organizations. Forecast verification relies on available measurements, news reports and social media information about impacts as well as available response reports.

In two interviews, forecasters commented that they were doing work that should belong to civil protection. In one interview this referred to summarizing response reports, in the other interview to assembling information required by emergency managers. The forecaster, in the latter case explained that civil protection agencies were not as involved in such project work as they were permanently tied up reacting to crises. This forecasting agency had broader responsibilities in water management, and the forecaster described it as frustrating to take initiative where they wanted emergency managers to be more involved. Forecasting agencies did not always have access to response reports. One forecaster described that they had limited access to response reports for forecast verification, and only got general reports from some agencies like fire brigades. However, often responses were handled by local authorities, which did not provide reports to the forecasting agency and in some cases did not create reports at all.

Forecasters were not the only ones describing such coordination issues. One emergency manager explained they were in the process of adapting emergency plans to be based on impact-warnings. This involved coordinating with the forecasting agency to translate EFAS information and national models to impact-based warning scenarios. The emergency manager explained how some forecasters had perceived EFAS as a threat to their position while EFAS was intended to improve forecaster's ability to identify scenarios for the impact warnings and thereby deliver more useful information to emergency managers. The emergency manager expressed that receiving EFAS had helped them in moving forward in collaborating with the forecasting agencies to receive impact information.

These projects to improve forecasting products and emergency planning thus require inputs both from forecasting agencies and civil protection agencies and are more difficult if the civil protection agencies or forecasting agencies do not participate. Similarly, plugging gaps in reporting by civil protection, as well as summarizing and sharing of reports with forecasting agencies would aid forecast verification. Different instantiations in the process model imply different distributions of responsibilities between forecasting agencies and civil protection agencies which need to be considered. For instance, moving toward forecasters providing decision-support would involve forecasters much more in discussing questions of emergency management. Emergency managers directly accessing EFAS and conducting their own assessments require appropriate support communication by the forecasting agency and, as highlighted, training to fulfil this role. Forecasting and civil protection agencies conduct drills and draw lessons after events to build and improve routines. If EFAS information is regularly used, partners should consider including the interpretation of EFAS information in such drills, as well as drawing lessons from its use during past events.

Partners' feedback to EFAS

The feedback that EFAS receives from partners depends on what information is available to partners, and to what extent they provide this to EFAS. In one interview, there were no routines around feedback, but forecasters were encouraged to provide feedback on a voluntary basis. In another interview, one forecaster described their organization's routine for providing feedback to EFAS. A forecaster would compare the warning issued by EFAS, to measurements from the nearest rainfall gauge and provide feedback on the accuracy of the magnitude, timing of the peak and the location of the EFAS notification. They did not report events missed by EFAS, however. One of the interviewed emergency managers also explained that they try to provide feedback to every notification. Another emergency manager explained feedback to EFAS was provided only by the forecasting agency. If partners use EFAS regularly and have verification data available, they should consider using it to fill in the EFAS feedback as well.

Communication flows and timing

During the additional evaluation interview with a forecaster, the forecaster described an issue where local authorities receiving warnings, complained that they get warnings from different organizations but were unsure what to expect based on these. The presentation of these different warnings was not consistent. One of the academic experts described a similar issue, where flood warnings and weather warnings issued by different organizations were using inconsistent iconography. The forecaster also emphasized that forecast users needed to be more familiar with interpreting the warnings, to avoid being overwhelmed with phone calls when issuing a warning. Authorities issuing warnings, like flood forecasting agencies and meteorological agencies may consider coordinating calls and harmonizing iconography to present warnings coherently and make them easier to interpret for recipients.

During the evaluation, a forecaster expressed interest in seeing the timing element to the different instantiations discussed. The main factor that may impact timing of steps in the process model, is whether guidance and coordination calls are optional or non-optional. In a scenario where decisions are taken without these calls, a warning may then be issued faster than where additional calls need to be conducted. Too many phone calls may complicate reacting to warnings with very little lead time. The alternatives to providing more support are then to improve the clarity of warning presentation and, as emphasized by a forecaster, to provide more training to forecast users. Of course, there are also challenges to providing training, like for instance people changing position frequently or if training would need to be provided to a very large group of forecast recipients. Partners thus need to find a good balance between these different strategies. The timing of support communication may also be improved through pre-warnings. Pre-warnings based on medium-range forecasts like EFAS could be used to improve the scheduling of support calls, by informing authorities earlier and then pre-scheduling calls. If available models perform well enough, EFAS partners can consider using EFAS for extending lead times on their warnings or establishing forecasting products for pre-warnings for this purpose.

The SOV principle and third-party partners

Another topic that came up during the follow-up interviews were differences regarding the implementation of the Single Official Voice Principle. Silingardi (2019, p. 177) notes that the principle is often not expressly implemented nationally. Across interviews, third party partners faced differing restrictions in terms of how they could use EFAS information. In case of the national civil protection authority which issued assessments to other civil protection authorities, emergency managers received EFAS as a third-party partner, but were not allowed to communicate EFAS information to authorities on other levels of government. This was explained through the SOV principle, as the decision to issue EFAS information to other authorities should be made by forecasting agencies. EFAS was then used for internal and European-oriented assessments, as well as clarifying communication with the forecasting agencies in case of questions. The other third-party partner emergency manager interviewed, operating on the local level, faced no such restrictions. In the other case, the regional emergency management agency also did not face such restrictions, as it receives EFAS as a full partner. One forecaster outlined that warning procedures were not strict, and it was less clear who should receive warnings or who a journalist seeking information about issued warnings should contact. Thus, the SOV principle is not applied by all partners, and where it is applied, arrangements and results seem to differ. When re-evaluating their use of EFAS information, third party partners facing restrictions must thus be kept in mind. In such a case EFAS partners could consider making arrangements with these third-party partners enabling them to communicate EFAS information. For instance, third party partners could send assessments based on EFAS information to the full partner who then has the authority to pass them on.

Availability of plans and connection to the wider FRG context

Finally, the availability of and development of emergency plans tied to flood warnings differed. In one case, standards for plans had been introduced across local authorities in recent years, as before plans had varied widely between local authorities and were not always present. In another interview, the emergency manager explained that they were coordinating with the forecasting agencies to adapt plans to impact information. Ultimately, bigger cities were meant to update flood plans themselves, while for smaller municipalities this was done by the regional civil protection organization. During one of the additional interviews, the forecaster explained that the decision to create flood emergency plans, linked to impact warnings had only recently been taken after a flood event. Before, only general emergency plans, and very few flood emergency plans in some regions had existed. This also highlights that when adapting the information communicated in warnings, this implies considerable planning effort in updating all the emergency plans. In addition, whether plans are available and how detailed they are may vary across countries, and even within the same country. This may be an example of trade-offs between different FRM strategies, as suggested by Hegger et al. (2016, p. 10): If an area at risk of flooding has not been flooded before or very rarely, because it was protected by other means, there may be no emergency plans available, and no readily available reference events (Alexander 2015, p. 17) to base the plan on.

The interview during which the relationships between different strategies was most visible, was with the local level emergency manager. This authority was performing a wide range of responsibilities for reducing local flood risk, including flood warning and civil protection responsibilities, but also creating spaces to store floods or operating flood barriers. The emergency manager described how FRM competed with other issues in local politics. Spaces for storing floods competed with housing pressures, closing flood barriers could lead to events being cancelled and complaints and building flood defences in low lying areas could collide with residents and commuters wanting to preserve the view. Precaution was highest after a flood event, when political will and acceptance for pre-emptive measures was highest. Next to how EFAS information is utilized in FEWS outcomes are then determined by these wider dynamics.

5.1 Limitations

In the following section, the limitations of this article and the developed model are outlined.

Generalizability, bias and missing perspectives

The model focusses on the European Union and conclusions thereby first and foremost apply to this context. For example, on a global level, data availability, the structure of the involved organizations as well as restrictions around the use of data differ more widely than in Europe. EFAS information is provided to all partners for free, as one forecaster emphasized. This may often not be the case for similar types of data elsewhere. Even within the European context, data availability differs, and monitoring networks are for example more extensive in central Europe as compared to Mediterranean countries, which also affects the performance of flood forecasts, including EFAS, as noted by a forecaster.

The model and discussion were based on 15 interviews, including agencies operating in FEWS in 7 countries. This is only a sample of EFAS partners (Copernicus Emergency Management Service 2022) which may be biased. Given the variance between countries and EFAS partners, it is likely, some variations of using EFAS are missing in the model. In particular, the perspective of emergency managers is less well covered. While three emergency managers were interviewed, the majority of interviews was conducted with flood forecasters. The emergency managers interviewed all had access to EFAS information, which most civil protection authorities do not have. Flood forecasters were not always able to describe how forecast users utilized warnings, as forecasting agencies were not always involved in these activities. Academic experts were also able to comment on aspects of civil protection. Still, the perspective of emergency managers is less well captured by the model.

The model considers communication flows to and decisions by flood forecasting and civil protection agencies, directly or indirectly receiving EFAS information. Not all types of EFAS partners were included, like for instance railway agencies. How they utilize EFAS information is not covered in the model, only flood forecasting, and civil protection organizations are. The ERCC and national partners using EFAS to coordinate supranational emergency response or aid activities or the connection to the pre-tasking of satellite images for response and recovery by the Copernicus rapid-mapping service are not included.

Abstractions made in the model

The model generalizes across EFAS partners by functions they perform but abstracts other aspects away. This decision was taken to keep the model manageable and clear, but of course it means losing some information. Next to the levels of government at which EFAS partners are situated, the model also abstracts warning dissemination to the public. This decision was taken, as the focus of the article was on the use of EFAS information, which is not disseminated to the public. Effective warning dissemination to the public is important for the FEWS to save lives and protect assets (Parker & Priest 2012) and thus an essential step to consider beyond the model.

As highlighted earlier, the model abstracts additional information used by forecasters, like for instance on tidal waves or snowmelt. The model also does not consider the role of local knowledge and experience, or what one academic expert termed empirical knowledge. This type of knowledge is important to finetune thresholds, appropriately interpret warnings and react to them. It can be affected by pressures like retirement, austerity cutbacks or losing volunteers and should be considered in partner's training, support communication and emergency planning strategies.

Finally, Civil Protection and forecasting agencies are heterogenous and often have different portfolios of responsibilities which are not captured in the model. In some cases, EFAS partners are hydrometeorological forecasting agency, which also issues meteorological forecasts and warnings whereas in other cases meteorological and hydrological forecasters work in separate agencies. Some forecasting agencies are part of environmental ministries and also responsible for water management more broadly. These differences are also true for civil protection authorities, which may be separate agencies, part of the ministry of the interior, or of local authorities. As highlighted in the discussion, these differences can affect how flood forecasters and emergency managers view their role, relative to other organizations.

Factors like the level of government or the precise actors fulfilling the different functions need to be specified when applying the model, which increases the effort needed to use it. A more thorough evaluation and extension of the model is therefore needed. To determine whether the model can fulfil the principle of economic efficiency, additional evaluation by applying the model would also be needed.

Process Modelling not established

Another limitation of the article is that process modelling, just as it is not established in the DRM domain (Peinel et al. 2012) is not established in FEWS. While some forecasting agencies and EFAS centres used workflows to coordinate processes, most activities are organized through written procedures and routines. Therefore, a domain specific modelling language known by model stakeholders could not be used. The EPC was used, as it is easy to understand and extend. During evaluation interviews, interviewees were able to follow and understand the explanation of the model. Providing a reference process model for using EFAS in national FEWS is then also a contribution of the article.

6 Conclusion

In this article, a reference process model was developed showing the communication of EFAS information in national early warning systems. The model was designed across two iterations of the DSR Cycle following Peffers et al. (2007). To design and evaluate the model 3 interview series for a total of 15 interviews were conducted with flood forecasters, managers at forecasting agencies and EFAS centres, emergency managers and academic experts. The model distinguishes three uses of EFAS information, using EFAS for warning and forecasting, using EFAS as a pre-warning and using EFAS for flood response. Within each of these uses, different alternatives for utilizing EFAS are highlighted. Both direct uses, as well as indirect use through communication flows is depicted. The model can aid the evaluation of EFAS usage and overcome barriers to its use for decision-making, by clarifying current use and comparing it to alternatives. As EFAS continues to improve, partners can reconsider extending their use of the system. Further evaluation is needed to extend the model to EFAS partners whose perspectives have not been covered so far. More thorough application of the model is needed to ascertain whether it can fulfil the principle of economic efficiency. The following section outlines possibilities for further research.

Process Modelling in FEWS

To the author's knowledge, while process modelling is beginning to garner attention in DRM research, no reference process for communicating risk information within FEWS has been proposed so far. Process modelling could aid hydrometeorological forecasting agencies and civil protection authorities communicate about and transform their processes using the same language. This can help overcome some of the barriers FEWS face, given the importance of coordination and communication between these agencies. The interviews revealed that some forecasting agencies and EFAS centres define workflows. EFAS centres utilize workflow management systems to coordinate processes. The use of process modelling to aid the coordination between forecasting agencies and civil protection authorities is then an avenue further research could explore.

Learning and multi-level governance

Another aspect to explore that emerged during the interviews is policy-learning from other countries and EFAS. In one case, a forecaster explained how the national flood forecasting service had been modelled on EFAS. Similarly, forecasters mentioned learning from other countries approach to using EFAS and providing Flood Early Warnings more generally. Further research could thus explore the impact of transnational projects and cooperation on the dynamic within the national FEWS.

Change dynamics and learning also took place on the subnational level, revealing dynamics of multi-level governance. In one case, a regional civil protection agency had been introduced to EFAS flash flood warning layer, through an EU project. Adapting to using EFAS information then shaped the dynamic between the civil protection organization and forecasting agencies. Forecasting agencies aid in the interpretation of EFAS and move toward providing impact-based flood warnings. Other civil protection agencies within this country are then also starting to move in this direction and exchanging experiences. EFAS alerts were then also received by local authorities in one case. Further research could examine how these multi-level governance dynamics affect EFAS, national FEWS and FRG more broadly.

The SOV principle and open data

One particular difference to examine relates to the application of the SOV principle across countries. In federal systems, the functions depicted in the model may be performed across several levels of the administration and information flows affected by the SOV principle. As highlighted in the discussion, the SOV principle is not applied consistently across countries. Further research could examine how different third-party partners use information and what restrictions they face across countries. Much of the data provided by Copernicus services is provided as open data. Further research could explore the tension between demands for open access versus restrictions around EFAS and other transnational risk information.

Risk governance and transnational information

In each organization covered by the interviews conducted for this article, EFAS information always entered national FEWS through assessment functions, comparing various information sources of information. Forecasting agencies often bundled EFAS with their own systems, by receiving EFAS information as a web map, and displaying it within their own systems. For emergency managers, systems like EU-anywhere (Centre de Recerca Aplicada en Hidrometeorologia 2022) provide a variety of information as well. This type of tool is also utilized outside of Europe, like for instance the Pacific Disaster Center's DisasterAWARE multi-hazard warning platform (Pacific Disaster Center 2022), or the Global Flood Awareness System providing EFAS-like information on a global scale (Copernicus Emergency Management Service 2022). There are also national portals combining information from various forecasting agencies within the country. Transnational risk measures and dashboards to visualize them are being developed across many domains, like for instance in the EU-inform project which covers a broad range of risks from natural disasters to conflict (European Commission Disaster

Risk Management Knowledge Centre 2022). Further research could compare how users assess and utilize these different sources of transnational risk information.

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