Can MCDA guide transdisciplinary endeavors? A framework applied to co-developing a flood forecasting system in West Africa

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Abstract. Climate change is projected to increase flood risks in West Africa. The EU Horizon 2020 project FANFAR co-designed a pre-operational flood early warning system (FEWS) for West Africa in workshops with 50–60 stakeholders from 17 countries, adopting Multi-Criteria Decision Analysis (MCDA). We aimed at: (i) designing a FEWS with West African stakeholders using MCDA; and (ii) evaluating participatory MCDA as a transdisciplinary process. To achieve aim (i), we used MCDA problem structuring and preference elicitation methods in workshops: stakeholder analysis, creating 10 objectives to be achieved by the FANFAR FEWS and 11 possible configurations. Experts predicted FEWS configuration performance, which we integrated with stakeholder preferences in MCDA, and tested in sensitivity analyses. Three FEWS showed good performance, despite uncertainty, and were robust across different preferences. For stakeholders it was most important that the FEWS produces accurate, clear, timely, and accessible flood risk information. To achieve aim (ii), we reviewed sustainability science and transdisciplinary research literature for common characteristics. Our framework emphasizes uncertainty and integrates interdisciplinary knowledge, which are crucial to the earth systems sciences. MCDA can well address both. We critically evaluated MCDA following the framework. The strength of MCDA lies in step 2: co-producing knowledge with stakeholders, providing a consistent methodology, and unambiguous, shared results. Participatory MCDA including problem structuring can contribute to step 1 of co-design, but does not well achieve step 3 of co-disseminating and evaluating results. We encourage colleagues to use the framework for guiding transdisciplinary hydrology research that engages with stakeholders and society.

1 Introduction

1.1 Floods in West Africa

West Africa is vulnerable to projected impacts of climate change, particularly concerning runoff quantities (Aich et al., 2016;Roudier et al., 2014). Climate change projections and mechanisms remain uncertain for West Africa, but there is growing evidence for increased frequency, magnitude, and impact of floods (Nka et al., 2015). West Africa is already heavily impacted by floods. Preliminary United Nations data estimate that 465 people died from floods in West and Central Africa in 2020. More than 1.7 million people were affected, 94’000 displaced, and 152’000 houses were destroyed (OCHA, 2020). Good flood early warning system (FEWS) help minimizing flood impacts (Perera et al., 2019); good means they give accurate, timely, and understandable information, and are affordable. Several FEWS have been set up in West Africa, some being very useful. However, none sufficiently meet stakeholder needs regarding: i) timeliness (e.g., annual frequency of PRESASS/PRESAGG forecasts; WMO, 2021); ii) coverage (systems propagating streamflow measurements cover small parts of West Africa and no ungauged basins, e.g., SLAPIS, OPIDIN, FEWS-Oti; Massazza et al., 2020); iii) up-to-date operational production without failures (e.g., interrupted production and access to SATH-NBA during the major 2020 floods; NBA, 2020); iv) accuracy (e.g., global modelling systems such as GloFAS; Passerotti et al., 2020); and v) openness and ownership (e.g., proprietary closed-source consultancy systems may limit the independence of West African stakeholders, and hence the FEWS' long-term sustainability). An overview of gaps, needs, and recommendations is provided by WMO (2020). Moreover, stakeholders assigned the lowest score to the overall effectiveness of FEWS in all but one West African country (Lumbroso et al., 2016).

1.2 Developing a FEWS with stakeholders in the FANFAR project

The EU Horizon 2020 project FANFAR (2018–2021) addressed these gaps by co-developing a pre-operational FEWS for West Africa (FANFAR, 2021). It included African and European consortium partners, and stakeholders across 17 countries of West and Central Africa. FANFAR relied on cooperation between hydrologists, information and communication technology (ICT) experts, decision analysts, and users (Andersson et al., 2020a). The FANFAR FEWS is currently based on three open-source hydrological HYPE models (Andersson et al., 2017;Arheimer et al., 2020) in a cloud ICT environment. It includes daily meteorological forecasting, data assimilation, hydrological forecasting, flood alert derivation, and distribution through Email, SMS, API, and an interactive visualization portal (https://fanfar.eu/ivp/). Rather than the technical system (Andersson et al., 2020b), this paper addresses stakeholder engagement in an iterative co-design process, which is needed to address FEWS development (Sultan et al., 2020).

To organize such a transdisciplinary endeavor involving many stakeholders, a comprehensive Multi-Criteria Decision Analysis (MCDA) process can be suitable (Belton and Stewart, 2002;Eisenführ et al., 2010;Keeney, 1982). It should include problem structuring methods (Rosenhead and Mingers, 2001). Participatory MCDA can help focus FEWS development such that it best meets stakeholder expectations. Indeed, MCDA has been used in flood risk management (reviewed by de Brito and Evers, 2016;Abdullah et al., 2021), but rarely as participatory process. Stakeholders were not even mentioned in a review of 149 papers (Abdullah et al., 2021). de Brito and Evers (2016) concluded that stakeholder participation was fragmented, despite being reported in 51% of 128 papers, i.e., stakeholders weighted objectives, but were not involved in the entire decision process. However, participation is extensively discussed in sustainability sciences (e.g., Caniglia et al., 2021;Norstrom et al., 2020) and transdisciplinary research (e.g., Jahn et al., 2012;Lang et al., 2012;Mauser et al., 2013;Schneider et al., 2019;Wuelser et al., 2021). With this paper we combine the two fields. We draw from literature to develop an evaluation framework, and apply it to the integrative MCDA process in FANFAR. To the best of our knowledge, we are not aware of systematic assessment of MCDA from the angle of transdisciplinary sustainability research.

2 Literature review, research questions

2.1 Sustainability science and transdisciplinary research frameworks

Disaster management increasingly acknowledges that FEWS development should closely involve users to increase its usefulness (adapted to needs) and effectiveness (e.g., enhance uptake; Basher, 2006;Bierens et al., 2020;UNISDR, 2010). This follows a trend calling for "collaborative action", "collaborative governance", and "co-production of knowledge". Sustainability science stresses that societal transformation is needed to address global environmental challenges. It requires close engagement of academia with stakeholders (e.g., Caniglia et al., 2021;Lang et al., 2012;Mauser et al., 2013;Norstrom et al., 2020;Schneider et al., 2019;Wuelser et al., 2021). Transdisciplinary research emphasizes collaboration between scientific disciplines, and practitioners (Jahn et al., 2012). It supports societal problem solving with "situated knowledge" for a problem in its socio-ecological context (Wuelser et al., 2021). Many transdisciplinary projects are being carried out. However, there is a lack of systematic integration and conceptualization of empiric evidence (e.g., Lang et al., 2012;Caniglia et al., 2021), and mechanisms of sustainability transformations are not well understood (Schneider et al., 2019;Wuelser et al., 2021).

Frameworks for collaborative governance consist of stages such as inputs, research processes, direct outputs, and further outcomes (Schneider et al., 2019). Earlier transdisciplinary frameworks emphasized iterative processes in phases: (i) forming a common research object (see Figure 1 in Jahn et al., 2012), problem framing, team building (see Figure 1 in Lang et al., 2012); (ii) co-creating solution oriented knowledge through collaborative research; (iii) applying co-produced knowledge (Lang et al., 2012), and evaluating its contribution to societal and scientific progress (Jahn et al., 2012). Similar steps were proposed for global sustainability problems, involving academia and stakeholders throughout (see Figure 3 in Mauser et al., 2013): (i) co-design with jointly framing the societal sustainability challenges, research definition, and implementation; (ii) co-production, including methodologically consistent scientific integration of interdisciplinary knowledge and dealing with uncertainty; and (iii) co-dissemination via scientific publications and products for different societal groups, transparent discussion of results, especially among groups of conflicting interests, and consequential action.

Recent frameworks shared similar elements, but used a different structure. Caniglia et al. (2021) suggested that research actions for sustainability create transformative change in three knowledge dimensions: (i) informing intentional design; (ii) enhancing shared agency by involving multiple actors; and (iii) enabling contextual realization in changing environments. The dimensions are further characterized by prescriptive knowledge (recommendations for better options), co-produced knowledge (collaboration with actors, incorporating their perspectives and interests), and situated knowledge (tailored to specific contexts; see Table 2 in Caniglia et al., 2021). From a practical perspective, four guiding principles for evaluating the quality and success of co-production processes were proposed (see Figure 1 in Norstrom et al., 2020): (i) context-based (situate process in context, place, or issue); (ii) pluralistic (recognize multiple ways of knowing and doing); (iii) goal-oriented (articulate clearly defined, shared goals); and (iv) interactive (ongoing learning among actors, active engagement, and frequent interactions).

Recently, 12 transdisciplinary projects were systematically evaluated to identify common characteristics, resulting in seven types of transferable knowledge (see Table 2 in Wuelser et al., 2021): (i) transdisciplinary principles (e.g., take practitioners on board); (ii) transdisciplinary approaches (e.g., joint problem identification, alliances with regional partners); (iii) systematic procedures (e.g., specific methodologies); (iv) product formats (communicate and use results in practice, e.g., capacity building); (v) experiential know-how (personal learnings, skills); (vi) framings (definitions, descriptions); and (vii) insights, data, and information (results). Similarly, 31 transdisciplinary projects were systematically analyzed to identify three generic mechanisms of societal impacts (see Figure 1 and Table 2 in Schneider et al., 2019): (i) promote systems, target, and transformation knowledge; (ii) foster social learning for collective action; and (iii) enhance competences for reflective leadership.

The last example stems from the earth systems sciences. Its starting point is a climate assessment case that provides conceptual insights, rather than firstly drawing from social science theories as most above literature (Lemos and Morehouse, 2005). Hereby, interactive models and iterative processes foster innovation and societal impact across three dimensions: (i) interdisciplinarity (effort of scientists from different disciplines to tackle complex problems, working together iteratively, or separately if needed); (ii) interaction with stakeholders (e.g., problem definition, testing and disseminating results, adapting research to user needs, building trust); and (iii) production of usable knowledge.

In this paper, we draw on the reviewed literature from sustainability science and transdisciplinary research to propose a framework for guiding and evaluating transdisciplinary projects. We specifically focus on requirements of hydrology research.

2.2 Multi-Criteria Decision Analysis (MCDA) in flood risk research

Methodological and epistemological perspectives in transdisciplinary research may be debated (Jahn et al., 2012), but in a project, consensus on methods and integrative concepts is needed (Lang et al., 2012). The FANFAR consortium agreed on MCDA as organizing framework to include stakeholders and design the FEWS for West Africa. MCDA is well suited to address this challenge and embraces various methodologies to support complex decisions (e.g., Belton and Stewart, 2002;de Brito and Evers, 2016). We chose Multi-Attribute Value Theory (MAVT; Eisenführ et al., 2010;Keeney, 1982) for reasons well documented in literature: (i) developing a complex FEWS requires many decisions such as identifying hydrological models and data sources to produce forecasts, or appropriate flood hazard thresholds, visualizations, and distribution channels to reach people. MCDA allows addressing such choices. (ii) To adapt the FEWS to stakeholder needs, collaboration with nonacademic partners is required. MCDA allows close stakeholder interaction, offering various methods for each stage of decision making (e.g., Eisenführ et al., 2010;Keeney, 1982;Marttunen and Hamalainen, 2008;Zheng et al., 2016;Marttunen et al., 2017). (iii) MAVT and Value Focused Thinking (Keeney, 1996) base decisions on the objectives that are of fundamental importance to stakeholders. (iv) To evaluate FEWS configurations, MCDA allows integrating different kinds of scientific and technical data from experts (e.g., forecast accuracy, development costs) with stakeholder preferences. Especially in case of conflicting interests, it can be helpful to disentangle stakeholder values from facts (Gregory et al., 2012a;Keeney, 1982). In complex decisions, not all objectives can be fully achieved. MCDA explicitly asks stakeholders which trade-offs they are willing to make. (v) MAVT and Multi-Attribute Utility Theory (MAUT) are mathematically very flexible. Usually linear additive aggregation is applied, but many non-compensatory models are possible, which may better represent stakeholder preferences (Haag et al., 2019a;Reichert et al., 2015;Reichert et al., 2019). (vi) MAVT/MAUT allow including various types of uncertainty, e.g., of expert predictions with probability theory, or stakeholder preferences with sensitivity analyses (Reichert et al., 2015;Haag et al., 2019b;Zheng et al., 2016). (vii) MCDA is done stepwise to reduce complexity and increase transparency.

MCDA is increasingly popular in hydrology and flood risk research. Our brief literature search revealed around 50 articles, but only few included stakeholders (Web of Science 25.08.2021; keywords: "MCDA" AND "hydrolog*" AND/OR "flood*"). This corroborates results of two reviews (de Brito and Evers, 2016;Abdullah et al., 2021). Both confirmed a significant growth in MCDA applications, especially for flood mitigation, while flood preparedness, response, or recovery phases were understudied. Most papers lacked uncertainty analysis and stakeholder participation (de Brito and Evers, 2016). We found that MCDA was mainly used as technical method to integrate indicators, e.g., for calibrating flood forecasting models (Pang et al., 2019). Recent methodologically interesting papers addressed MCDA coupled with artificial intelligence (Pham et al., 2021), machine learning (Nachappa et al., 2020), or portfolio decision analysis (Convertino et al., 2019). Combining GIS with MCDA is a trend, also in hydrology. Examples include flood risk assessment focusing on uncertainty (Tang et al., 2018), and flood risk analyses producing risk maps (e.g., Ronco et al., 2015;Samanta et al., 2016).

This applied literature lacks stakeholder integration (de Brito and Evers, 2016). Exceptions are a MCDA concept to improve urban resilience in flood risk management (Evers et al., 2018), and a participatory case study for flood vulnerability assessment (de Brito et al., 2018). In cases with participation, stakeholders mainly only assigned weights (de Brito and Evers, 2016). Our search confirmed lacking stakeholder involvement. The few exceptions shortly presented weights, without discussing the participatory process (e.g., Ronco et al., 2015). However, several papers stated that MCDA results are highly susceptible to model assumptions, especially weights (de Brito and Evers, 2016). For instance, sensitivity of MCDA results to weight variability was assessed with global sensitivity analysis (Tang et al., 2018). Concluding our review, hydrology and flood risk research lack literature that understands MCDA as a stakeholder engagement process. To increase decision making quality and implementation success, MCDA applications require uncertainty analysis and stakeholder participation (de Brito and Evers, 2016).

Here, we document participatory MCDA that involves stakeholders throughout the process, including uncertainty. Taking the lens of sustainability science and transdisciplinary research, we apply the proposed framework to critically evaluate MCDA.

2.3 Aims, research gaps, and research questions

In this paper we follow two complementary aims: (1) support and document FEWS development for West Africa using a comprehensive MCDA process in close interaction with stakeholders, and including uncertainty; and (2) evaluate participatory MCDA as a transdisciplinary process. To achieve these aims, an inter- and transdisciplinary approach is needed.

As outlined in sect. 1.1, there is a lack of FEWS at West Africa scale that sufficiently meet user needs. To interact with stakeholders (from West Africa in the FANFAR case), a transdisciplinary approach is needed. We thus reviewed the transdisciplinary and sustainability science literature to identify frameworks for guiding transdisciplinary projects (sect. 2.1). Despite many shared characteristics, we found differences between frameworks, and only few took the perspective of the natural and earth systems sciences. Moreover, this literature acknowledges a lack of conceptualization and systematic integration of empiric evidence. MCDA can support decisions about suitable FEWS configurations (sect. 2.2). MCDA can integrate different types of data and stakeholder interests, and can deal with uncertainty. However, literature indicates that participatory MCDA integrating stakeholders throughout the process, and focusing on uncertainty, is rarely done in flood risk research. Moreover, the call of this Special Issue on contributions of transdisciplinary approaches to hydrology and water resources management emphasizes: "(…) we need to remind ourselves that a scientific decade on change in hydrology and society requires the perspectives of those disciplines that have traditionally been concerned with society (…). While interdisciplinary conversations have been happening to some extent, transdisciplinary endeavors remain largely undocumented" (Carr et al., 2021). Finally, whether MCDA is suitable to guide transdisciplinary processes in all phases remains an open question. These research gaps lead to following research questions, grouped under the two aims:

Aim (1): Define what constitutes a good FEWS for West Africa using a participatory MCDA process, and document empirical evidence from the FANFAR project, hereby contributing to knowledge production, learning, and scientific praxis in hydrology.

- **RQA:** What characterizes a good regional FEWS for West Africa? Is it possible to identify a robust FEWS configuration, despite uncertainty (of expert predictions about FEWS performance and MCDA model) and possibly different preferences of stakeholders regarding what the FEWS should achieve?

Aim (2): Evaluate the suitability of participatory MCDA as a transdisciplinary process.

- **RQB:** What are main characteristics of existing frameworks from transdisciplinary research and sustainability science that are useful for guiding and evaluating collaborative transdisciplinary projects in hydrology research?
- **RQC:** How suitable is a participatory decision analysis process based on MCDA for guiding large transdisciplinary projects? What worked well or less well in FANFAR? Is the proposed framework useful for this type of evaluation?

3 Methods

3.1 Transdisciplinary Multi-Criteria Decision Analysis (MCDA) process

A typical MCDA process starts with joint problem framing (Fig. 1). For better understanding, we added three main steps of our transdisciplinary framework to the overview (see Table 3); problem framing belongs to co-design step 1. Not part of MCDA were building the collaborative research team (step 1a), defining research questions, methodological framework (step 1b), and boundary object (FEWS for West Africa; step 1c; Table 3). However, this was part of the FANFAR project with joint proposal writing and a kick off meeting with European and West African consortium partners (sect. 3.1.1). As first step of the MCDA process that includes problem structuring, we did a stakeholder analysis (e.g., Grimble and Wellard, 1997;Lienert et al., 2013;Reed et al., 2009), which is often neglected in MCDA. Identifying stakeholders is crucial in any participatory project. Main identified stakeholders that participated in the workshops were representatives from hydrological services, emergency management agencies, river basin organizations, and regional expert agencies. Together with these priority stakeholders, we identified objectives ("What is of fundamental importance to be achieved by a FEWS?") and options ("Which FEWS configurations are potentially suitable to achieve objectives?"). To support first MCDA steps, diverse Problem Structuring Methods (PSMs) are available (Rosenhead and Mingers, 2001). It is common to combine MCDA with PSMs (reviewed by Marttunen et al., 2017). Similar PSMs as used in FANFAR, were described in a wastewater infrastructure planning example (Lienert et al., 2015). The next steps 5–7 in MCDA (Fig. 1), belong to the transdisciplinary co-production step 2. Hereby, research produces new knowledge in continuous exchange between scientists from different disciplines and stakeholders. A transdisciplinary process is often iterative (e.g., Jahn et al., 2012;Lang et al., 2012), captured in FANFAR with several cycles of workshops with decision makers, end users, and stakeholders ("stakeholders" hereafter) to test, discuss, and improve the pre-operational FEWS. In the co-dissemination and evaluation step 3, new knowledge is critically reflected, integrated, and disseminated, captured in step 8 of MCDA (Fig. 1). After summarizing the workshops (sect. 3.1.1), we focus on the MCDA steps (sects. 3.1.2–3.1.8).We present MCDA methods such that they are easily adaptable to other transdisciplinary projects, e.g., in hydrology, and provide extensive details as blueprint in the Supplementary Information.

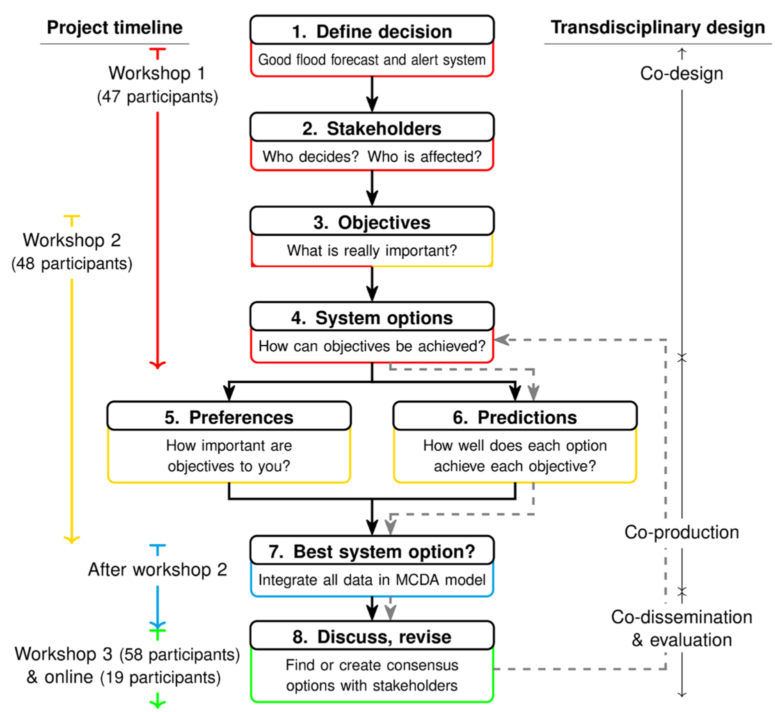

Figure 1: Multi-Criteria Decision Analysis (MCDA) was carried out stepwise in the FANFAR project. Explanations see text.

3.1.1 Co-design workshops in West Africa

We carried out three workshops in West Africa, and a FANFAR consortium kick off meeting (Norrköping, Sweden, 17–18 January 2018). A fourth workshop was replaced by two half-day online workshops due to COVID-19 (20–21 January 2021), and a final online workshop (1 June 2021). The workshops are documented in reports (FANFAR, 2021;Lienert et al., 2020). At each workshop, West African stakeholders presented the rainy season flood situation in their country and their experience with the FANFAR FEWS. Each workshop hosted extensive technical sessions for experimentation with the latest FEWS configuration, and structured technical feedback. Between workshops, the FEWS was adapted to meet requests as well as possible (Andersson et al., 2020a). We also conducted sessions with emergency managers, e.g., about their understanding of flood risk representation to improve FEWS visualizations (Kuller et al., 2020). Here, we focus only on interactions at the core of MCDA.

The first workshop (Niamey, Niger, 17–20 September 2018) hosted 47 participants from 21 countries, including European and African consortium members, and representatives from regional and national hydrological service and emergency management agencies from 17 West and Central African countries. Main aim was initiating the co-design process. For MCDA, we used problem structuring (Fig. 1): stakeholder analysis (sect. 3.1.2); identifying fundamentally important objectives of stakeholders (sect. 3.1.3), and FEWS configurations that meet objectives; sect. 3.1.4). The second workshop (Accra, Ghana, 9–12 April 2019) hosted 48 participants from 21 countries. For MCDA, we consolidated objectives and elicited participants' preferences regarding achieving these objectives (sect. 3.1.6). Additionally, we collected preference data on the importance of objectives from each stakeholder with questionnaires. This provided interesting insights into preference formation over time (Kuller et al., in prep.). For the third workshop (Abuja, Nigeria, 10–14 February 2020), participant numbers increased to 58, including representatives from WMO (World Meteorological Organization; https://public.wmo.int/), ECOWAS (Economic Community of West African States; https://www.ecowas.int/), and 16 West and Central African countries. We discussed main MCDA results. During a last online workshop, which was attended by 10–19 participants (varying numbers due to internet connection problems), stakeholders completed a survey, providing some feedback for MCDA (sect. 3.1.9).

3.1.2 Stakeholder analysis

For the stakeholder analysis (Grimble and Wellard, 1997;Reed et al., 2009), we followed Lienert et al. (2013). Workshop participants filled in a pen and paper questionnaire in French or English, assisted by two experts. The survey was completed in 2.5 hours by 31 participants in 18 groups (for countries). After receiving information, the participants completed two tables, one for identifying key West African organizations that produce and operate FEWS, and one for downstream stakeholders (i.e., "Who might play a role because they use information from such systems in society?"). Each table contained eight tasks: (1) listing key organizations or stakeholders; (2) specifications (e.g., names); (3) their presumed main interests; (4) why they might use FEWS; and (5) appropriate distribution channels. We used a 10 point Likert scale, asking participants to (6) rate the importance of considering each listed stakeholder in the FANFAR co-design process; (7) the presumed influence (power) of each stakeholder for implementing the FEWS; and (8) how strongly each would be affected by the FEWS performance level.

We cleaned the raw data and categorized stakeholders according to: forecast/alert producers or users, decisional level, sector, and perceived main interest (details see Silva Pinto and Lienert, 2018).

3.1.3 Generating objectives and attributes

Generating objectives is key to MCDA (Belton and Stewart, 2002;Eisenführ et al., 2010;Keeney, 1982), since this choice can alter results. Value Focused Thinking guides this step by focusing on what is fundamentally important to stakeholders (Keeney, 1996). However, simply asking is insufficient, and often too few (Bond et al., 2008;Haag et al., 2019c) or too many objectives are produced; we refer to the guidelines in Marttunen et al. (2019). Our stepwise procedure started at the FANFAR kick off meeting in Sweden and continued in the first two West African workshops (details see Lienert et al., 2020). In the first workshop, one stakeholder group individually used an interactive online survey to first brainstorm, then select objectives from a master list (Haag et al., 2019c). Individuals in a second group used the same procedure as pen and paper survey, assisted by a moderator. The third group used a means-ends network in a moderated group discussion to find consensus objectives (Eisenführ et al., 2010). Each participant (respectively group) ranked and rated objectives according to importance. Objectives were discussed in the plenary and the most important ones were chosen by majority vote. We post processed objectives to avoid common mistakes such as double counting, overlaps, or means objectives (Eisenführ et al., 2010). MCDA objectives are only useful if they discriminate options (FEWS configurations in our case), and we dismissed those not fulfilling this requirement. In the second workshop, we presented a revised list of 10 most important objectives, including a clear definition of the best and worst possible case for each (see attribute descriptions; sect. SI-2.4.1). For instance, the FEWS being available in *2.3 Several languages* is the best case, and only in English the worst (note: names of objectives, attributes, FEWS configurations, and stakeholder groups are given in Italics; see Fig. 2; Table 1). After discussion, stakeholders agreed on the final objectives as basis for MCDA. To operationalize objectives, attributes (synonym indicators) are required (Eisenführ et al., 2010). These were developed by experts from the FANFAR consortium. In most cases, we constructed attributes from several sub-attributes (sect. 3.1.5). Sub-attributes or attributes were transformed to a value using marginal value functions (sect. 3.1.6).

3.1.4 Generating FEWS configurations

Different plausible FEWS configurations were generated in the first workshop, in three moderated group sessions. Two groups used the “Strategy Generation Table” (Gregory et al., 2012b;Howard, 1988), and one “Brainwriting 635” (Paulus and Yang, 2000) combined with “Cadavre Exquis” (write words on paper, fold, give to next person). The Strategy Generation Table allowed pre-structuring FEWS elements (e.g., observed variables, forecast production models, language). Stakeholders chose elements forming suitable FEWS configurations with help of questions: “The most easy to use FEWS”, or the “Most robust FEWS working well given West African boundary conditions (e.g., internet or power supply problems)”. Brainwriting 635 allowed for interactive brainstorming, using the same questions. We discussed all FEWS configurations in the plenary. As part of post processing, FANFAR consortium members created technically interesting FEWS configurations. We provide details in the Supplementary Information for readers unfamiliar with the methods (sect. SI-1.1).

3.1.5 Predicting performance of each FEWS configuration

Part of the MCDA input data are scientific predictions (Fig. 1), based on estimates or models of the performance level for each objective (Eisenführ et al., 2010). We used expert estimates (O'Hagan, 2019) by interviewing FANFAR consortium members in July–August 2019. First, experts developed attributes (sect. 3.1.3), mostly constructed from sub-attributes. They estimated the outcome of each FEWS configuration for each (sub-) attribute, i.e., the likely level of each attribute (e.g., operation costs) and gave uncertainty ranges. For constructed attributes, we integrated the predictions of the sub-attributes into one value using a weighted sum (weights defined by experts; sect. 3.1.6). We aggregated the uncertainty of each sub-attribute into a single uncertainty distribution with 1'000 Monte Carlo simulations. To characterize the resulting aggregated uncertainty, we used a normal distribution with mean (of Monte Carlo simulation), and standard deviation (¼ of the 95% confidence interval from simulation) as input in the MCDA (sect. 3.1.7).

Example: Objective *1.1 High accuracy of information* consists of three sub-attributes: KGE index for 1, 3, and 10 day forecasts (Kling-Gupta Efficiency; Gupta et al., 2009). The KGE is one possible accuracy index for hydrological model evaluation, e.g., to estimate the error of predicted vs. observed values. For each FEWS configuration and lead day, the expert estimated the KGE. The KGE index number was transformed to a value, ranging from 0 (worst) to 1 (best), with a nonlinear marginal value function, elicited from the expert. We aggregated the lead day values into a single value [0:1] with a weighted sum, where the accuracy of the 1 day forecast received a weight of 0.5, the 3 day forecast 0.4, and 10 day forecast 0.1. Details for predicting system performance (expected attribute level) see sect. SI-2.4.

3.1.6 Eliciting stakeholder (or expert) preferences

Marginal value functions. Subjective preferences of stakeholders enter the MCDA model on equal footing to expert predictions (Fig. 1). Preference elicitation is an important, sensitive step during which many biases can occur (Montibeller and von Winterfeldt, 2015). It is crucial to follow recommendations (Eisenführ et al., 2010). Marginal value functions convert the attribute levels for each objective (e.g., KGE index for *1.1 High accuracy of information*) to a common scale from 0 (worst possible achievement of this objective) to 1 (best achievement). This allows integrating attributes with different units into one model, e.g., KGE index with operation costs (€ y^{-1}), and development time (days). As default, a linear marginal value function can be used. However, nonlinear value functions usually better capture preferences. In FANFAR, most attributes are technical, requiring expert knowledge. We thus elicited shapes of value functions from experts (sect. 3.1.5; details, including figures of value functions, see sect. SI-2.4.1). For each sub-attribute, we mostly created seven evenly spaced levels (worst, very bad, bad, neutral, good, very good, and best). Experts then assigned attribute numbers (e.g., KGE index for 3 day forecasts) to each level. We transformed attribute levels to [0:1] values using linear interpolation between levels. As example, the KGE index ranges from minus infinity (worst case, value 0) to 1 (best case, value 1; Table SI-8). For each sub-attribute, we elicited a nonlinear marginal value function (Fig. SI-5), allowing aggregation into one value. Because we already used elicited nonlinear value functions to construct the composite attribute, we used a linear value function for these in MCDA (sect. 3.1.7).

Weights. In the second FANFAR workshop, we elicited weights from five groups, according to language (French F, English E) and professional background (Emergency managers, Hydrologists). The two French speaking groups used the Swing method (Eisenführ et al., 2010): eight emergency managers (group *1. Emergency-F*), and 11 hydrologists (two sub-groups *2A.* and *2B. Hydrology-F*). The two English speaking groups used an adapted Simos' revised card procedure (Figueira and Roy, 2002;Pictet and Bollinger, 2008), hereafter Simos card: 14 hydrologists (*3. Hydrology-E*), and three emergency managers (*4. Emergency-E*). We elicited weights from three AGRHYMET experts with Simos card (*5. AGRHYMET-E*). Stakeholders can be uncertain about their preferences, or groups may disagree. For Swing, we avoided forcing participants to reach group consensus and encouraged discussion of diverging opinions, resulting in a range of weights. We took the mean as main weight and considered strong deviations (difference in weights > 0.2 compared to mean) in sensitivity analyses (sect. 3.1.8). For Simos' card, two additional weight sets resulted from eliciting a range for one variable. The moderator recorded important comments to inform sensitivity analyses (Table SI-3). For French speaking hydrologists, two diverging preference sets emerged from the start, which we analyzed separately (*2A, 2B*). For interested readers, we give details of standard MCDA weight elicitation (sect. SI-1.2). To check for the validity of the additive aggregation model (sect. 3.1.7), we shortly discussed implications in the weight sessions using elicitation procedures from our earlier work (Haag et al., 2019a;Zheng et al., 2016).

3.1.7 MCDA model integrating predictions and preferences

The MCDA model integrates expert predictions with stakeholder preferences, and calculates the total value of each FEWS configuration (= alternatives; Eisenführ et al., 2010). A finite set of FEWS alternatives $A = \{a, b, \dots\}$ are evaluated regarding the predicted outcomes on every objective (respectively attribute). We denote predicted outcomes (sect. 3.1.5) as $x_a = (x_{a,1}, \dots, x_{a,n})$, with $x_{a,i}$ the level of an attribute i that measures a predicted consequence of FEWS a *(or b, c, ...)*. The total value $v(x_a)$ of FEWS a is calculated with a multi-attribute value function, $v\left(x_{a,1}, \dots, x_{a,n}, \Theta\right)$. The resulting total value $v(x_a)$ of each FEWS is between 0 (all objectives achieve worst level) and 1 (all objectives achieve best level given the attribute ranges). A rational decision maker chooses the FEWS with the highest value. Commonly, an additive model is used:

$$\boldsymbol{v(x_1, x_2, \dots, x_n, \Theta) = \sum_{i=1}^{n} w_i \cdot v_i\,(x_i, \theta)} \qquad \text{(Eq. 1)}$$

with parameters $\Theta = (w_1, \dots, w_n, \theta)$, where w_i is the weight of attribute i, with $0 \leq w_i \leq 1$, and $\sum_{i=1}^{n} \boldsymbol{w_i} = \boldsymbol{1}$, (Eq. 2)

and where $v_i(x_i, \theta)$ is the value for the predicted consequence x_i of attribute i of FEWS a. This value is inferred with help of the marginal value function (sect. 3.1.6).

While easy to understand, the additive model entails strong assumptions, e.g., that objectives are preferentially independent (Eisenführ et al., 2010). Increasing evidence indicates that many stakeholders do not agree with model implications (Haag et al., 2019a;Reichert et al., 2019;Zheng et al., 2016). Additive aggregation implies that good performance on one objective can fully compensate for poor performance on another. In the FANFAR weight elicitation sessions, we asked stakeholders, using some examples, whether they agree with objectives being preferentially independent, and as consequence with the full compensatory effect. In all five groups this was not the case. We therefore used a non-additive model with less strict requirements, the weighted power mean with an additional parameter γ that determines the degree of non-compensation:

$$\boldsymbol{v}(\boldsymbol{x_1}, \boldsymbol{x_2}, \dots, \boldsymbol{x_n}, \boldsymbol{\Theta}) = \left(\sum_{i=1}^{n} \boldsymbol{w_i} \cdot \boldsymbol{v_i}(\boldsymbol{x_i}, \boldsymbol{\theta})^{\boldsymbol{\gamma}}\right)^{1/\boldsymbol{\gamma}} \qquad \text{(Eq. 3)}$$

If $\gamma = 1$, we are back to the additive model in Eq. (1). We used $\gamma = 0.2$, based on stakeholder input (sect. 3.1.6), close to a weighted geometric mean ($\gamma \to 0$). We visualize implications of the power mean in sect. SI-1.3 (details see Haag et al., 2019b).

We calculated MCDA results in our new open source software "ValueDecisions" (Haag et al., subm.), based on R (R Core Team, 2018), earlier R scripts developed in our group (e.g., Haag et al., 2019b), and R "utility" package (Reichert et al., 2013). R scripts were rendered as web application for ValueDecisions with the "shiny" package (Shiny, 2020). We used R for additional analyses: aggregating uncertainty of sub-attributes, weight visualization, and statistical analysis of sensitivity analyses.

3.1.8 Uncertainty of predictions and preferences

Uncertainty of predictions: Probability theory is used in MAVT (Reichert et al., 2015). We defined uncertainty distributions from expert predictions for each attribute (sect. 3.1.5). We calculated aggregated values of each FEWS configuration across all objectives (sect. 3.1.7), drawing randomly from the attributes' uncertainty distributions in 1'000 Monte Carlo simulation runs. We analyzed rank frequencies: how many times in 1'000 runs each FEWS configuration achieved each rank.

Sensitivity analyses of aggregation model and weights: Local sensitivity analyses are common to check the sensitivity of MCDA results to diverging preferences (e.g., Eisenführ et al., 2010;Zheng et al., 2016;Haag et al., subm.). We checked aggregation models and weights. We used setting S0 as default, comparing it with a separate MCDA for each setting with changed preference input parameters (settings are summarized in results Table 2; details see sect. SI-1.4). For each setting, we compared mean ranks of FEWS configurations from 1'000 Monte Carlo simulation runs with the default MCDA (S0). We used nonparametric Kendall's τ correlation coefficient (Kendall, 1938) to measure rank reversals (as in Zheng et al., 2016). To test the aggregation model (sect. 3.1.7), we recalculated the MCDA for other reasonable models (Haag et al., 2019a; settings S11–S14; Table 2). For weights, we changed the weight of one objective, while ratios of all others were kept constant and renormalized. For more method explanations see Eisenführ et al. (2010); details for readers not familiar with MCDA see sect. SI-1.4. Consistency checks during weight elicitation with group *1. Emergency-F* revealed an inconsistency, and strongly different weights (Fig. SI-3). We tested it in sensitivity analysis S21 (Table 2). For Swing weights, stakeholders stated ranges, which we tested if the difference between the maximum or minimum from the average weight exceeded $\Delta = 0.02$ (S22). For Simos' card, we tested alternative weight sets resulting from ranges (S23). It is common to test interesting objectives by doubling the elicited weight. We did this for *2.3 Several languages*, because its importance might have been underestimated (S31).

Cost-benefit visualizations are an additional way to check the robustness of results (e.g., Liu et al., 2019). We used standard setting S0 without prediction uncertainty (Table 2) for this visual analysis. For reasons of space, we refer to sect. SI-2.9.

3.1.9 Discuss results with stakeholders, feedback

We discussed first MCDA results in the third stakeholder workshop. Workshop four was carried out online due to COVID-19, and we were not able to thoroughly discuss results. We did assess stakeholder perceived satisfaction with FEWS performance during the 2020 rainy season with an online survey, asking following questions for each objective: (a) How much does the FANFAR FEWS currently fulfill this objective? (b) Would you use the FEWS in future if it remains as is? (c) What is the minimum acceptable to you? This means: below which level would you NOT use the FEWS? (details see sect. SI-1.5).

3.2 Conceptual framework for transdisciplinary process

Based on the reviewed sustainability science and transdisciplinary research literature (sect. 2.1), we identified common elements. We aimed to set up a useful framework that allows evaluating transdisciplinary processes in hydrology research, including the MCDA in FANFAR. We included elements that are crucial for practice-oriented projects such as FANFAR, and are especially relevant to the earth systems sciences, e.g., climate assessment (Lemos and Morehouse, 2005).

4 Results

The MCDA results are ordered as in the Methods (sect. 3.1) for answering research question RQA (sect. 4.1–4.8). We present the evaluation framework in sect. 4.9 (RQB). Based on MCDA results and the framework, we address RQC in the Discussion.

4.1 Stakeholder analysis

Of 249 stakeholders listed by workshop participants, 68 distinct types remained after data cleaning (details see Silva Pinto and Lienert, 2018). Stakeholders perceived to have high influence and being highly affected by the FANFAR FEWS were national entities for disaster management, water resources, and infrastructure, who were well represented in FANFAR (details Table SI-4). Specific organizations were also perceived as highly important and affected, e.g., "Autorité du Bassin de la Volta" (ABV), who participated in workshops, and the consortium member AGRHYMET, representing 13 West African states. Other important/affected parties were mainly stakeholders receiving forecasts and alerts such as NGO's, electricity utilities, dam managers, and the agricultural sector. The Red Cross and environmental protection agencies were perceived to have slightly lower importance/affectedness, among others. Civil society (e.g., communities) would be strongly affected, but have limited decisional influence on developing the FEWS. In contrast, the media, industry, and commerce were perceived to have more influence, but would not be strongly affected. Such outlier stakeholders could potentially provide a different view to the FEWS.

4.2 Objectives and attributes

Objectives covered issues of fundamental importance to stakeholders in view of a *Good FEWS* for West Africa (Fig. 2). Some objectives concerned quality requirements, grouped as *1. High information accuracy and clarity,* and *2. Good information* *access* such as accounting for language diversity. Aspects of *3. Low costs* and *4. High sustainability* were also important, e.g., *42. Skilled labor* in West Africa, capable of maintaining, operating, and accessing the FEWS. Each objective is characterized by an attribute, for operationalizing the objectives' achievement (Fig. 2; attribute calculations see sect. SI-2.4).

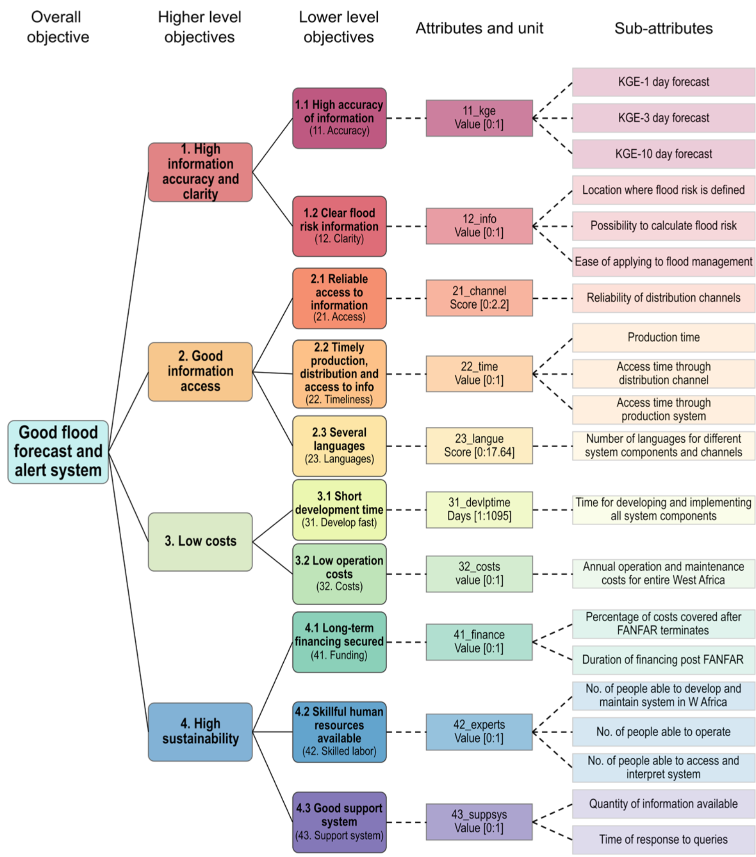

Figure 2. Objectives hierarchy. From left to right: overall objective, four higher level fundamental objectives, 10 lower level fundamental objectives (short names in brackets) and corresponding attributes, attributes' unit (usually a value) and range [square brackets], from worst (usually value = 0) to best (usually value = 1). Most attributes were constructed from sub-attributes (far right).

4.3 FEWS configurations

Stakeholders generated six FEWS configurations in workshop sessions (b to g; Table 1). Experts of the FANFAR consortium developed five configurations (h to k) to cover important technical aspects such as using refined hydrological models, e.g., redelineation and recalibration of the World Wide HYPE model to West Africa (Andersson et al., 2020b), and including earth observations (EO) from satellites. FEWS were constructed in separate sessions with experts from AGRHYMET for the forecast production system, and with stakeholders for the user interface IVP (Interactive Visualization Portal). They were combined to form plausible combinations of various FEWS elements (summary of important features in Table 1; all FEWS elements see Tables SI-6 and SI-7). Configuration *a. Status quo* represents roughly the state of the initial FEWS version, when stakeholders started experimentation and giving feedback in the first workshop.

Table 1. Overview of 11 FEWS configurations. Selected main characteristics: recent hydrological observation data types (HydObs; WL: water level, Q: river discharge, EO: Earth Observations) & meteorological input/forcing data (MetF; HydroGFD; HydroGFD3 (Berg et al., 2020; improved version); HydroGFD-WA: HydroGFD2 adjusted by West African meteorological observations; Am: American meteorological forecasts (e.g., GFS); Ens: ECMWF ensemble meteorological forecasts); hydrological models (WWH: World-Wide HYPE); forecast output variables (Q: river discharge; WL: water level, P: precipitation; E: evaporation; SM: soil moisture, WQ: water quality); data download (Excel: table for selected station); distribution channels (Web: web visualization; H-TEP: login to H-TEP to download data; FTP: FANFAR and national FTP; API: Application Programming Interface; SoMed: Social Media e.g., WhatsApp; ConMed: conventional media e.g., radio, TV; Tradit: traditional word of mouth) & automatization (Automatic: automatic push of data to distribution channels; Manual: automatic processing with manual control of distribution by operator); flood hazard reference threshold types (RP Sim: return period based on simulations; RP Obs: return periods based on observations at gauged locations; HistY: selected historic year; Local: user defined thresholds for specific location); language of user interface (En: English; Fr: French; Pt: Portuguese; Ar: Arabic).

Name	Configuration	Hydrological observations & meteorological forcing	Hydrological models	Forecast output variables	Data download	Distribution channels & automatization	Flood hazard thresholds	Language
a. Status quo	Least resources for development: no new features, status quo	HydObs: none; MetF: HydroGFD2	Niger HYPE	Q	None	Web; Automatic	RP Sim	En
b. Resource friendly	Least resources for users (e.g., skilled personnel, stable internet and power)	HydObs: in situ WL, Q; MetF: HydroGFD3	WWH	Q, WL, P, E, SM	Excel, maps, graphs	Web, H-TEP, SMS, Email, SoMed, ConMed, Tradit; Manual	RP Sim, RP Obs, HistY, Local	En, Fr, Pt, Ar
c. User friendly	Most easy to use for producing and interpreting forecasts and alerts	HydObs: EO WL; MetF: HydroGFD2	Niger HYPE	Q, WL, P, E	Excel, graphs	Web, SMS, SoMed, ConMed, Tradit; Automatic	RP Sim, HistY	En, Fr, Pt
d. Fast alerts	Fastest system for producing and distributing forecasts and alerts	HydObs: EO WL; MetF: HydroGFD2	Niger HYPE	Q	None	Web, SMS, Email, SoMed, ConMed, Tradit; Automatic	RP Sim	En
e. Consensus	Highest consensus: system elements that West African stakeholders mostly agreed on	HydObs: in situ WL, Q, EO WL; MetF: HydroGFD-WA, Am, Ens	Niger HYPE, WWH	Q, WL, P, E, SM	Excel, maps, graphs	Web, H-TEP, SMS, Email, SoMed, ConMed, Tradit; Manual	RP Sim, HistY	En, Fr, Pt

f. Robust	Most robust in West Africa: works despite problems in e.g., data collection	HydObs: EO WL; MetF: HydroGFD2	Niger HYPE, WWH	Q, WL, P, E, SM	Excel, maps, graphs	Web, H-TEP, SMS, Email, SoMed, ConMed, Tradit; Manual	RP Sim, RP Obs, HistY, Local	En, Fr, Pt, Ar
g. Attractive	Most attractive to West African stakeholders: includes many desired features, similar to *h. Fully equipped*, but simpler distribution	HydObs: in situ WL, Q, EO WL; MetF: HydroGFD-WA, Am, Ens	Niger HYPE, WWH	Q, WL, P, E, SM, WQ	Excel, maps, graphs	Web, H-TEP, SMS, Email, SoMed, ConMed, Tradit; Manual	RP Sim, RP Obs, HistY, Local	En, Fr, Pt, Ar
h. Fully equipped	Fully equipped: all system elements, except recalibrated HYPE models	HydObs: in situ WL, Q, EO WL; MetF: HydroGFD-WA, Am, Ens	Niger HYPE, WWH	Q, WL, P, E, SM, WQ	Excel, maps, graphs	Web, H-TEP, FTP, API, SMS, Email, SoMed, ConMed, Tradit; choice (Automatic or Manual)	RP Sim, RP Obs, HistY, Local	En, Fr, Pt, Ar
i. Calibrated	Recalibrated HYPE models	HydObs: none; MetF: HydroGFD2	Recalibrated WWH	Q, WL, P, E, SM	Excel, maps, graphs	Web, H-TEP, SMS, Email, SoMed, ConMed, Tradit; Manual	RP Sim	En, Fr, Pt
j. Calibrated + EO	Recalibrated HYPE models and EO data	HydObs: EO WL; MetF: HydroGFD2	Recalibrated WWH	Q, WL, P, E, SM	Excel, maps, graphs	Web, H-TEP, SMS, Email, SoMed, ConMed, Tradit; Manual	RP Sim	En, Fr, Pt
k. Calibrated + EO + Insitu	Recalibrated HYPE models and EO data and in situ data	HydObs: in situ WL, Q, EO WL; MetF: HydroGFD2	Recalibrated WWH	Q, WL, P, E, SM	Excel, maps, graphs	Web, H-TEP, SMS, Email, SoMed, ConMed, Tradit; Manual	RP Sim	En, Fr, Pt

4.4 Predicted performance of each FEWS configuration

Based on expert predictions but excluding stakeholder preferences, no FEWS configuration achieved best levels of all objectives (Fig. 3; details see sect. SI-2.4, raw input data for MCDA modelling Table SI-30). This illustrates the impossibility to design a perfect FEWS, given the inherent trade-offs between achieving objectives. For instance, the status quo pre-operational FEWS *a. Status quo* achieved the highest values for objective *31. Develop fast (short development time)*, and *32. Costs*, but scored low on many others such as *11. Accuracy, 12 Clarity, 21. Access, and 22. Timeliness* of information. FEWS achieving high levels for objectives of *1. High information accuracy and clarity* cannot well achieve *31. Develop fast* at low *32. Costs*. Therefore, it is not possible to clearly determine the "best" FEWS based on only the predicted performance (Fig. 3). We require stakeholder input about the importance of objectives (sect. 4.5, sect. 4.6).

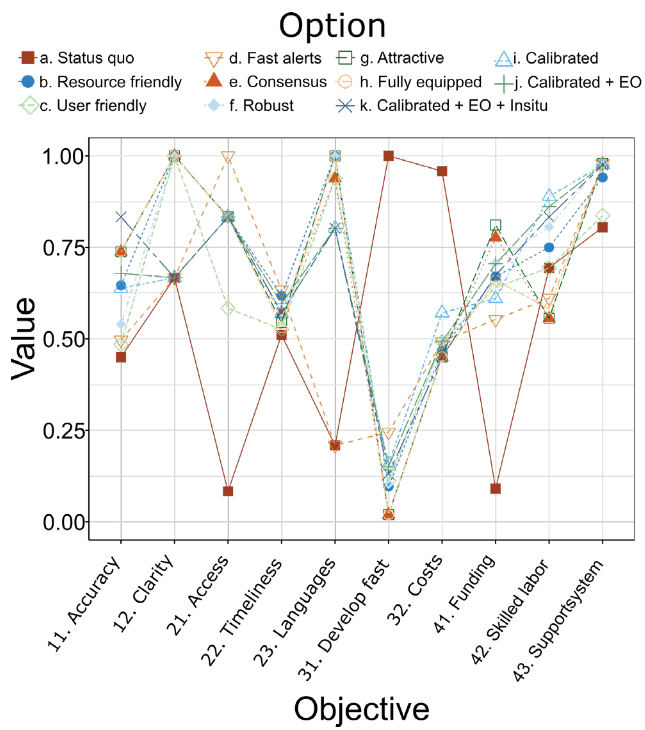

Figure 3. Predicted value (y-axis) of 11 FEWS configurations (options a–k; symbols) for 10 objectives (x-axis), based on expert predictions, but not including stakeholder preferences. Value 1: this FEWS configuration achieved the best level of this objective; 0: FEWS achieved worst level, given the ranges of underlying attributes (i.e., it is a relative scaling from best to worst).

4.5 Stakeholder preferences

The elicited weights (w) for the four higher level objectives were similar for all groups (w = total bar length; Fig. 4), except for the French speaking emergency managers (*1. Emergency-F*). These gave a high weight (w = 0.25) to *3. Low costs*, which was least important for the others (0.1–0.12). They reasoned that all four higher level objectives are equally important in emergency situations with a connected chain of events. In contrast, the higher level objectives *1. High information accuracy* *and clarity*, and *2. Good information access* were usually most important for the other groups. There were some notable differences in importance of lower level objectives. Again, group *1. Emergency-F* was exceptional in assigning much lower weights to objectives they considered unimportant (objectives *23, 31, 41, and 43*). They argued that the goal in emergencies is to save lives, and FEWS development should focus on achieving fast access to flood alerts (*22. Timeliness*; w = 0.21) and on personnel that can deal with this information (*42. Skilled labor*; w = 0.25). Weights in the other groups were more balanced (details sect. SI-2.6). There was varying agreement about weights within a group, reflected in the length of error bars (Fig. 4).

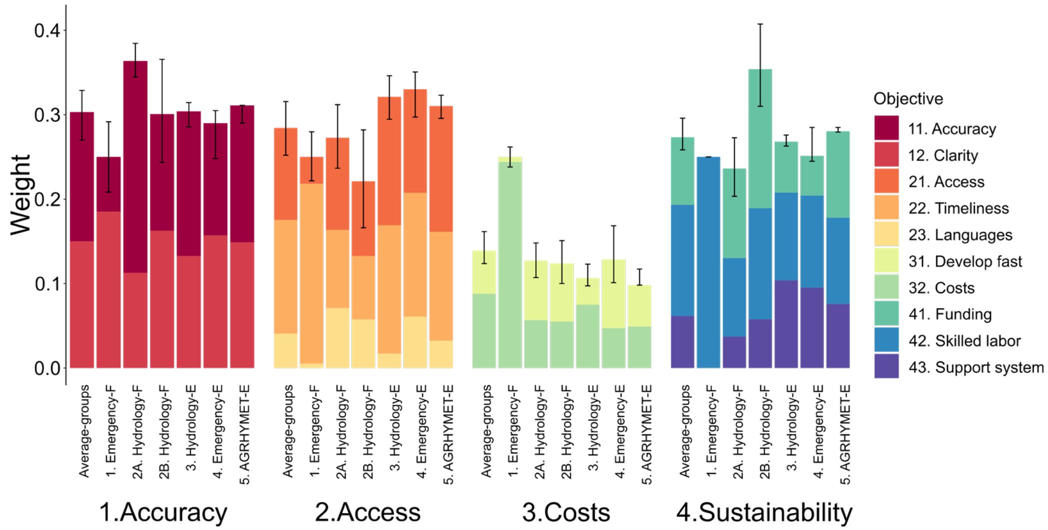

Fig. 4. Weights (y-axis) assigned to higher level objectives (blocks, *1. Accuracy*, *2. Access*, etc.) colored by weights of lower level objectives (*11. Accuracy*, *12. Clarity*, etc.), averaged over all six stakeholder groups (*Average-groups*), and for each group (*1. Emergency-F, 2A. Hydrology-F*, etc; x-axis). Error bars: uncertainty of elicited preferences, i.e., the sum of uncertainties of all lower level objectives within the branch of the respective higher level objective. Per definition all weights of a group sum up to 1.

4.6 MCDA model results

No FEWS configuration clearly outperformed the others for all stakeholder groups in the standard MCDA (setting S0; Table 2) that did not consider uncertainty (Fig. 5; details see Table SI-32; Table SI-33). The FEWS at the beginning of the project (*a. Status quo*) achieved lowest total values ($v < 0.46$) and last ranks for all stakeholder groups, except group *1. Emergency-F* ($v = 0.64$, rank 5). This is caused by their different weight preferences. All other FEWS generally reached high values for all groups, with small differences between groups. The total value ranged from $v = 0.55$ in the worst case (*d. Fast alerts* for group *2A. Hydrology-F*) to 0.70 (*b. Resource friendly* for *3. Hydrology-E*). This FEWS *b. Resource friendly* seemed somewhat better than the others, achieving a high value for all groups ($v = 0.65$–0.70), thus reaching the first rank for all, again with exception of group *1. Emergency-F*, for which it still achieved the second rank. For better understanding [0,1] values can be interpreted as percentages, and *b. Resource friendly* achieved 65–70% of the ideal case over all objectives in all stakeholder groups. FEWS configurations *f. Robust*, *i. Calibrated*, *j. Calibrated + EO*, and *k. Calibrated + EO + Insitu* also performed well (0.63–0.70) for all groups, while *c. User friendly*, and *d. Fast alerts* achieved the lowest values (0.55–0.64).

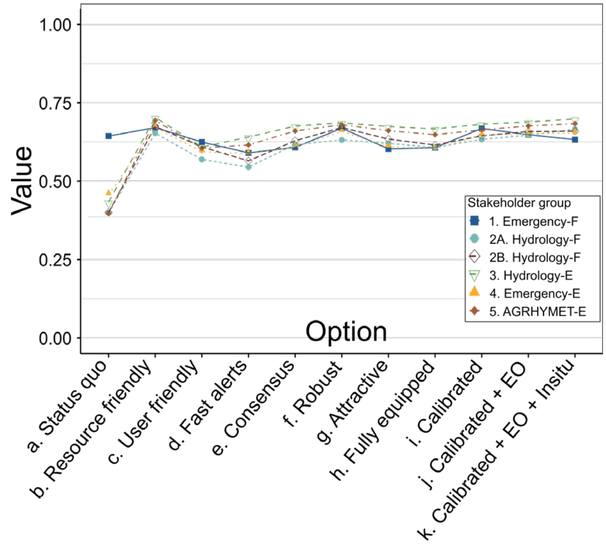

Figure 5. Total aggregated value (y-axis) of 11 FEWS configurations (x-axis) for six stakeholder groups (symbols), without uncertainty. Higher values indicate that they better achieved the objectives, given expert predictions and stakeholders' preferences.

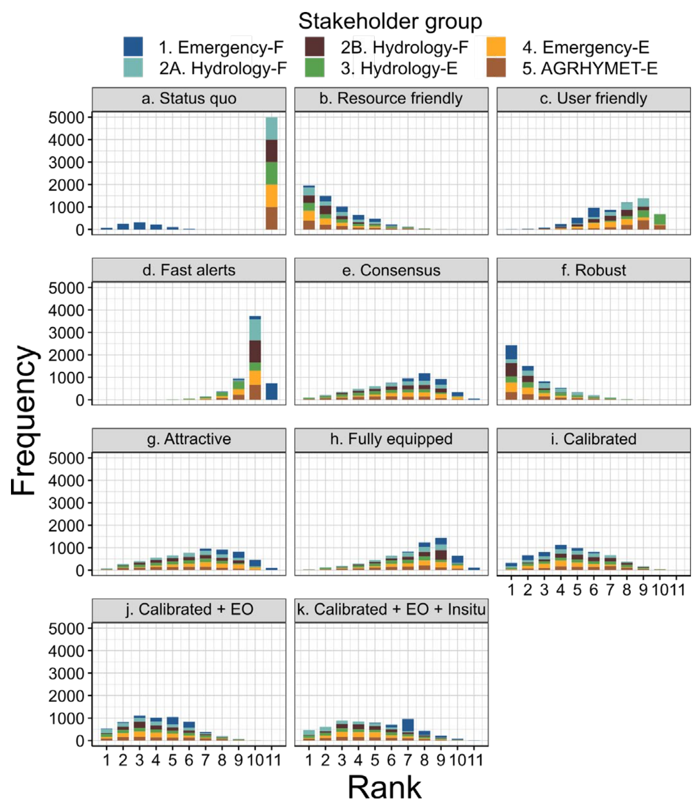

Figure 6. Ranks of 11 FEWS configurations including uncertainty of expert predictions. Frequency (y-axis): how often each FEWS (blocks, *a. Status quo*, *b. Resource friendly*, etc.) achieved rank (1: best rank, 11: worst; x-axis) in each model run, for each stakeholder group (stacked bars). 1'000 Monte Carlo simulation runs drawing from uncertainty distributions of attribute predictions.

Including the uncertainty of expert predictions in MCDA with Monte Carlo simulation clarified results. The FEWS *b. Resource friendly* and *f. Robust* performed well, achieving highest ranks for all stakeholder groups in 1'000 simulation runs (Fig. 6; details Table SI-34). The FEWS *i. Calibrated*, and *j. Calibrated + EO*, achieved good to medium ranks for most groups in most runs. Poor performance was achieved by *a. Status quo* (except group *1. Emergency-F*), and *d. Fast alerts*, which hit the last ranks in most simulation runs. The remaining FEWS performed somewhere in between.

4.7 Sensitivity analyses of stakeholder preferences

FEWS performance was not sensitive to most model changes (Table 2). The least changes in rankings occurred between the standard MCDA (S0) and sensitivity analyses of extreme weight ranges elicited from stakeholders (S22–S232; Table 2): Kendall's τ rank correlations were high, ranging from 0.86–1 (1 = identical ranking of all FEWS). Doubling the weight of *23. Languages* (S31) hardly impacted rankings of any stakeholder group. Greater changes occurred using other models. The difference between the standard MCDA (S0) and changed aggregation models increased, the more the aggregation parameter γ increased from 0 (geometric mean; S12), over mixture models (S13, S14), to 1 (additive model; S11). Rank correlations were still relatively high between the additive model and S0 (0.53–0.86). Importantly, rankings of the best-performing FEWS, *b. Resource friendly* and *f. Robust* did not change (sect. SI-2.8). For other configurations, including *i. Calibrated*, some differences were greater, depending on groups. The greatest changes occurred for alternative weights (S21) in group *1. Emergency-F*. Interestingly, this moved the rankings and values of FEWS to those of all other groups, this group no longer being an outlier, and e.g., *a. Status quo* clearly performing worst also for *1. Emergency-F* (Fig. SI-40). Cost-benefit visualizations confirmed that *b. Resource friendly*, *f. Robust*, and *i. Calibrated* are suitable consensus FEWS (see sect. SI-2.9 for reasons of space).

Table 2. Results sensitivity analyses. Setting S0: default with elicited preferences of stakeholder groups and weighted power mean model, Eq. (3). Setting S11–S14: effect of other aggregation models (varying γ). S21–S22: uncertainty of Swing weights. S231–S232: uncertainty of Simos' card weights. S31: increase (possibly underestimated) weight. S11–S31: all other parameters as S0. Columns group 1–5: Kendall's τ rank correlation coefficient between ranks of FEWS in main MCDA (setting S0) and ranks resulting from MCDA using other settings (S11–S31) for stakeholder groups (e.g., group *1. Emergency-F*). Column mean: correlation between S0 and average rank over all groups for which analysis was done. Note: S21 was only done for group *1. Emergency-F* (i.e., mean = group correlation). Kendall's τ 1: identical ranks; 0: no correlation; –1: inverse relationship; –: not applicable. Kendall's τ from 0.81–1.00: underlined, indicating very good agreement between changed setting and S0; τ from 0.61–8.80: dotted underlined.

		Stakeholder group						
Setting	**Parameter change definition**	**1**	**2A**	**2B**	**3**	**4**	**5**	**Mean**
S0	Default. MCDA for all six stakeholder groups; $\gamma = 0.2$; see Methods, eq. (3)							
S11	Additive model all groups; $\gamma = 1$	0.86	0.64	0.60	0.64	0.53	0.75	**0.67**
S12	Weighted geometric mean all groups; $\gamma \to 0$	0.96	0.78	0.93	1.00	0.82	0.93	**0.90**
S13	Mixture model; $\gamma = 0.5$	0.93	0.78	0.67	0.75	0.75	0.75	**0.77**
S14	Weighted power mean; $\gamma = 0.8$	0.89	0.67	0.64	0.64	0.53	0.75	**0.69**

S21	Alternative weight set for group *1. Emergency-F*	0.31	–	–	–	–	–	**0.31**
S22_11_min	Weight ranges with Δ > 0.02 from average weight for *11. Accuracy*; minimum weight	0.96	–	0.96	–	–	–	**0.96**
S22_11_max	*11. Accuracy*; maximum weight	–	–	1.00	–	–	–	**1.00**
S22_12_min	Weight ranges with Δ > 0.02 from average weight for *12. Clarity*; minimum weight	–	–	1.00	–	–	–	**1.00**
S22_12_max	*12. Clarity*; maximum weight	0.86	–	0.86	–	–	–	**0.86**
S231	Alternative weights from ranges of Z min	–	–	–	0.89	0.89	0.89	**0.89**
S232	Alternative weights from ranges of Z max	–	–	–	0.96	–	–	**0.96**
S31	Double weight of *23. Languages*	0.96	1.00	0.93	0.93	0.89	1.00	**0.95**

4.8 Stakeholders' perceived satisfaction with current FEWS

Participant numbers in the online workshop varied from 10–19 due to connection problems, which are frequent in West Africa, and related dropouts. The survey was filled out by 12 participants (12/19 = 63%), resulting for 10 objectives in 10 x 12 = 120 responses to each question. Most respondents perceived current performance as sufficient for all objectives, based on the direct question about future use of the FANFAR FEWS (b), and the inferred difference (c minus a) between how much the FEWS fulfills the respective objective (a) and the minimum acceptable level (c). Across all objectives, 79 responses were positive, 16 negative, and 25 did not answer question b. For the most important objective, *11. Accuracy*, all respondents would use the current FEWS in future (Fig. 7). However, four (of 12) respondents indicated that the FEWS does not currently meet their minimum acceptable performance requirements. This result is representative of results for all objectives (details sect. SI-2.10).

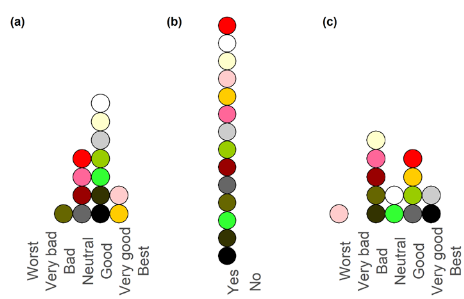

Figure 7. Stakeholder perceived satisfaction with FANFAR FEWS performance in the 2020 rainy season for objective *11. Accuracy*. Questions: (a) How much does the FEWS currently fulfil this objective? (b) Would you use the FEWS in future if it remains as is? (c) What is the minimum acceptable to you? Colored dots represent unique respondents (N = 12; 63% of 19 participants).

4.9 Results conceptual framework for transdisciplinary process

The reviewed literature from sustainability science and transdisciplinary research revealed that many characteristics are shared between different authors (sect. 2.1). We included these in our proposed own framework (Table 3). However, some elements received less attention in this social science oriented literature, which are highly relevant to the earth system sciences: explicit consideration of uncertainty and the interdisciplinary effort needed for tackling technically complex problems (Lemos and Morehouse, 2005;Mauser et al., 2013). Our framework follows a stepwise timeline, as proposed by many (Jahn et al., 2012;Lang et al., 2012;Mauser et al., 2013). We used the terminology by Mauser et al. (2013): (i) co-design; (ii) co-production, and (iii) co-dissemination of knowledge (to which we added evaluation), involving academia and stakeholders throughout. For each phase, we included elements appropriate for hydrology research for guiding and evaluating transdisciplinary processes.

Table 3. Conceptual framework for transdisciplinary research based on literature: (1) co-design, (2) co-production, and (3) co-dissemination of knowledge (terminology from Mauser et al., 2013), used to assess the MCDA process in the FANFAR project.

ID	Step	Explanation	Literature examples
1	**Co-design**	**Joint problem framing**	
1a	Build collaborative research team	Include structures enabling participation from the start, e.g., use stakeholder mapping; aim at legitimacy of team; include bridging organizations or knowledge brokers to increase trust	(Lang et al., 2012;Wuelser et al., 2021;Norstrom et al., 2020)
1b	Define research questions, methodological framework	Aim for balanced problem ownership from science and practice; define meaningful, shared goals, and measures of success	(Lang et al., 2012;Mauser et al., 2013;Jahn et al., 2012;Wuelser et al., 2021;Lemos and Morehouse, 2005;Norstrom et al., 2020)
1c	Define boundary object	Translate problem into boundary object that allows re-integrating insights into societal implementation and scientific body of knowledge; "transformation knowledge" on how to make change e.g., with measures and tools	(Lang et al., 2012;Jahn et al., 2012;Schneider et al., 2019)
2.	**Co-production**	**Conducting integrated research to produce new knowledge; continuous exchange among scientists from different disciplines, and with stakeholders**	
2a	Apply integrative (scientific) methods	Facilitate differentiation of different bodies of knowledge by using appropriate systematic procedures that ensure methodological consistency of research process	(Mauser et al., 2013;Wuelser et al., 2021;Lang et al., 2012;Jahn et al., 2012)
2b	Interdisciplinary collaboration	Integrate knowledge of scientists from different disciplines; avoid conflicting methodological standards	(Mauser et al., 2013;Lemos and Morehouse, 2005;Jahn et al., 2012;Norstrom et al., 2020)
2c	Explicitly consider uncertainty	Especially relevant in natural science problems addressing long time horizons (e.g., climate change)	(Mauser et al., 2013)

2d	Integrate practice stakeholders in iterative process	Ensure appropriate roles, range of perspectives and skills, and context-based research; avoid discontinuous participation and vagueness of results that conceal potential conflicts	(Caniglia et al., 2021;Lang et al., 2012;Lemos and Morehouse, 2005;Norstrom et al., 2020)
2e	Pluralistic principle/ social learning	Create shared understanding across multiple axes (e.g., disciplines, sectors, countries, gender); recognize values of people; foster training and capacity building	(Norstrom et al., 2020;Schneider et al., 2019;Caniglia et al., 2021;Wuelser et al., 2021)
3	**Co-dissemination and evaluation**	**Integrate and disseminate knowledge among research and societal groups in appropriate, relevant way; transparent discussion, critical reflection, and consequential actions**	
3a	Two-dimensional integration	Review, discuss, and revise outcomes from societal and scientific perspective, e.g., prescriptive knowledge (recommendations about more desirable options)	(Lang et al., 2012;Caniglia et al., 2021;Mauser et al., 2013)
3b	Generate targeted products	Translate results for scientific progress (e.g., generalizability), and real-world problem solving (e.g., relevance, scaling up results, alliances, actions in specific contexts, products such as maps, manuals, information for policy makers); knowledge transfer by scientists and societal actors	(Lang et al., 2012;Jahn et al., 2012;Wuelser et al., 2021;Caniglia et al., 2021;Lemos and Morehouse, 2005;Mauser et al., 2013)
3c	Evaluate societal and scientific impact	Reference back to success factors (step 1b); impact can be defined in many ways, e.g., research quality, media attention, download rates, communities of practice, social networks, capacity building, education, concrete products, changing people's lives; longer-term impacts are often not measurable	(Lang et al., 2012;Jahn et al., 2012;Norstrom et al., 2020;Schneider et al., 2019;Lemos and Morehouse, 2005)

5 Discussion

The discussion follows the research questions (sect. 2.3). RQA was confirmed: we found robust FEWS configurations despite large uncertainty and different stakeholder preferences (sect. 5.1). We discuss our experience with MCDA regarding uncertainty and eliciting stakeholder preferences (sect. 5.1.2). To answer RQB, we presented main characteristics of transdisciplinary and sustainability science frameworks (sect. 4.9), proposing a framework for guiding and evaluating transdisciplinary processes (Table 3). Using our framework, in RQC we analyzed the MCDA process for guiding large transdisciplinary projects (sect. 5.2). For step 1, co-design and joint problem framing, the FANFAR project met various requirements, which could not be attributed to MCDA (sect. 5.2.1). However, if MCDA is broadly understood as a participative process that includes problem structuring, it can be very suitable for identifying stakeholders and guiding them to focus on objectives for achieving a joint boundary object, the FEWS. For step 2, co-production of new knowledge, MCDA is appropriate (sect. 5.2.2). Core strengths of MCDA allow integrating scientific knowledge from different disciplines in a consistent framework and handling uncertainty. MCDA invites stakeholders to clearly formulate their preferences and identifies consensus FEWS configurations. Step 3, co-disseminating knowledge and evaluation, can only partly be achieved by MCDA (sect. 5.2.3). MCDA produces concrete, prescriptive knowledge: a suitable FEWS configuration. However, MCDA is not appropriate for other aspects such as producing and implementing real-world solutions, or impact evaluation. Insights and recommendations are summarized in Table 4.

5.1 Finding robust FANFAR FEWS configurations (RQA)

5.1.1 Main MCDA results

As the most important practical result to RQA, we identified three FEWS with good overall performance (Fig. 5). This would be difficult without MCDA, given the uncertainty of expert estimates and the model (Fig. 6). Moreover, trade-offs between objectives had to be made (Fig. 3), and stakeholders had different preferences concerning the importance of objectives (Fig. 4). One well-performing FEWS, *b. Resource friendly*, was created by stakeholders in the first workshop. They chose FEWS components requiring the least resources for West Africa such as skilled personnel, good internet connection, or stable power supply (Table 1). Similarly, stakeholders created *f. Robust* to reliably work under difficult West African conditions related to collecting in situ data and distributing information via various channels. The third FEWS *i. Calibrated* was created by FANFAR consortium members using refined HYPE models (e.g., adjusted delineation and parameter calibration; Andersson et al., 2020b), but excluding earth observation and in situ data (included in FEWS *j* and *k;* Table 1). All three best FEWS achieved 63–70% of all objectives in all stakeholder groups. We consider this a very good value, given the existing trade-offs. These FEWS were robust (i) when including the uncertainty of expert predictions with Monte Carlo simulation (Fig. 6); (ii) in sensitivity analyses of the aggregation model and stakeholders' weight preferences (Table 2); and (iii) in dominance checks in cost-benefit visualizations (sect. SI-2.9). Interestingly, these three FEWS did not incorporate more advanced features: a FEWS that meets stakeholder preferences primarily needs to work accurately and reliably under difficult West African conditions.

5.1.2 Dealing with uncertainty of predictions, preferences, and model assumptions

Attributes operationalize objectives (Eisenführ et al., 2010). Seemingly trivial, this is often challenging. We illustrated this for the KGE index for 1, 3, and 10 day forecasts to measure objective *11. Accuracy* (sect. 3.1.5). The uncertainty of expert predictions was relatively large for e.g., *11. Accuracy*, *22. Timeliness*, or *42. Skilled labor*, but small to inexistent for e.g., *12. Clarity*, and *23. Languages* (Fig. SI-30). The resulting overall uncertainty affected results less than expected (Fig. SI-35).

The weights indicated that most groups preferred a FEWS producing accurate, clear, and reliable information, reaching recipients well before floods (*11. Accuracy, 12. Clarity, 21. Access*; *22. Timeliness*; Fig. 4), and West African countries need the capability to handle this information (*42. Skilled labor*). We captured differences within groups with uncertainty ranges or separate preference sets (e.g., subgroups *2A, 2B*; sect. SI-1.2.3; sect. SI-2.6). The French speaking emergency managers (*1. Emergency-F*) had different preferences compared to all others. All groups regarded several languages as unimportant in weight elicitation, despite discussing in the plenary that language diversity is crucial. When asked to make trade-offs, they were willing to give up language diversity to achieve accuracy. They were also willing to trade-off higher operation and maintenance costs (except *1. Emergency-F*) and development time in return for receiving a functioning, precise FEWS.

Including the uncertainty of expert estimates and stakeholder preferences in MCDA can blur results. For FANFAR, including the uncertainty of predictions helped to *better* distinguish between FEWS performances (Fig. 6), compared to the standard analysis without uncertainty (Fig. 5). FEWS configurations *b. Resource friendly* and *f. Robust* consistently achieved the first ranks in 1'000 simulation runs, and e.g., *i. Calibrated* good to medium ranks. However, some FEWS such as *k. Calibrated + EO + Insitu*, ranked last in numerous runs (Fig. 6), despite achieving good values when uncertainty was disregarded (0.63–0.70; Table SI-33). Ranking last in most runs, *a. Status quo* and *d. Fast alerts* would be an imprudent choice.

Local sensitivity analyses (e.g., as Zheng et al., 2016) confirmed that *b. Resource friendly*, *f. Robust*, and *i. Calibrated* are robust choices. Changing stakeholder preferences hardly changed MCDA results compared to our standard model (S0; Table 2). Doubling the weight of *23. Languages* (S31) did not affect results in any group, thus avoiding costly translations as priority. Operation and maintenance costs would have been another candidate for doubling the weight, but was covered by the high weight of group *1. Emergency-F*. In this group, sensitivity analyses on weight ranges given by group participants with a different opinion (S21; Table 2) changed the results so that they aligned with results of the other stakeholder groups. This increases our confidence that the three proposed FEWS are a good consensus. Moreover, the additive MCDA aggregation model (Eq. (1); sect. 3.1.7) impacted the FEWS rankings (Table 2). As standard, we assumed non-additive aggregation (Eq. 3), close to a weighted geometric mean model, based on feedback in weight elicitation sessions. After discussing examples, all groups stated that poor performance on an important objective should not be compensated by good performance on others, a main implication of additive aggregation. This confirms that the additive model can unintentionally violate stakeholder's preferences (e.g., Haag et al., 2019a;Reichert et al., 2019;Zheng et al., 2016). Thus, additive aggregation may not be the best model, despite its popularity in MCDA applications. For FANFAR, sensitivity analyses sufficed to conclude that additive aggregation has an effect, but does not alter rankings of the best FEWS. We can safely conclude that the three proposed FEWS are suitable. We emphasize that the FEWS was continuously improved throughout the project, also after eliciting stakeholder preferences.

5.2 Suitability of the MCDA process for guiding large transdisciplinary projects (RQC)

We critically evaluate a participatory MCDA for guiding a large transdisciplinary project following our proposed framework (Table 3). We focus on important aspects of MCDA in a hydrology context, summarizing main points in Table 4.

5.2.1 Evaluating the co-design step "joint problem framing"

MCDA does not fully meet all requirements of this step. ***Building the collaborative research team*** cannot be attributed to MCDA, although it was achieved by the FANFAR project (step 1a, Table 3). Two key West African stakeholders were consortium partners from the start: AGRHYMET (mandated by 13 West African states and ECOWAS to provide e.g., operational flood warnings), and NIHSA (Nigerian Hydrological Services Agency). This follows a decade of collaboration between SMHI and AGRHYMET. Building alliances with regional partners is a transdisciplinary approach identified across projects, and may lead to follow-up partnerships (Wuelser et al., 2021). ***Trust building*** is crucial, and AGRHYMET is clearly a ***bridging organization or knowledge broker*** between research and implementation (Norstrom et al., 2020;Wuelser et al., 2021;Lemos and Morehouse, 2005). FANFAR was co-led by West African partners and engaged stakeholders in workshops, meeting the principle of creating ***knowledge tailored to specific contexts*** (Caniglia et al., 2021;Norstrom et al., 2020). However, this cannot be attributed to MCDA, nor ***defining the research questions*** (step 1b), or ***boundary object*** (step 1c, Table 3). The boundary object was to produce an operational FEWS, which allowed stakeholders to commit (Jahn et al., 2012). Scientists and stakeholders both aimed to achieve this goal, which helped overcoming unbalanced ownership (Lang et al., 2012). The FANFAR consortium agreed to use MCDA as ***integrative methodological framework*** (1b) to achieve this goal and integrate different scientific disciplines (Lemos and Morehouse, 2005;Mauser et al., 2013;Lang et al., 2012). MCDA is one possible useful, stringent, and integrative methodology to produce ***transferable knowledge*** (Wuelser et al., 2021).

Narrowing the perspective to the concrete project with West African stakeholders, MCDA emphasizing early problem structuring is helpful (Marttunen et al., 2017;Rosenhead and Mingers, 2001). ***Taking practitioners on board*** from the start and avoiding insufficient legitimacy or underrepresentation of actors is crucial (Lang et al., 2012;Wuelser et al., 2021). Stakeholder mapping or social network analysis are suitable to identify those to involve (Norstrom et al., 2020;Lang et al., 2012). As first step of MCDA, we carried out ***stakeholder analysis*** (step 1a, Table 3), which is rarely done (9% of 333 reviewed MCDA papers; Marttunen et al., 2017). We used relatively simple questionnaires (sect. 3.1.2) to discover who has influence or is affected by a FEWS (Grimble and Wellard, 1997;Lienert et al., 2013;Reed et al., 2009). We identified 68 distinct stakeholder types (sect. 4.1). In workshops, we included hydrologists from 17 countries, and key supranational organizations such as AGRHYMET who produce flood information (Table SI-4; details see Silva Pinto and Lienert, 2018). Main receivers of FEWS information also participated: emergency managers from every country. Thanks to their experience, we elaborated the alert dissemination chain and elements of effective FEWS (Kuller et al., 2021). We identified missing parties, e.g., agriculture, industry, or humanitarian aid organizations. Some provided informal feedback on the FEWS through social media. We did not invite them because more than 50 participants in workshops is ineffective. Indeed, ***pluralistic co-production*** while ***keeping processes manageable*** remains a challenge (Norstrom et al., 2020;Lang et al., 2012).

Problem structuring is decisive because MCDA results critically depend on objectives and options (i.e., FEWS configurations Marttunen et al., 2017;Rosenhead and Mingers, 2001). These MCDA steps were carried out in the first workshop (Fig. 1; sects. 3.1.3, 3.1.4). They helped define ***shared goals and a success measure*** (e.g., Norstrom et al., 2020; step 1b, Table 3): to find a FEWS that achieves the objectives. Following Value Focused Thinking (Keeney, 1996), we first generated objectives in small groups using different methods (sect. 3.1.3). This ensured a broad diversity and helped avoid the “group think bias” (Janis, 1972). We are confident that we captured the most important 10 objectives that cover fundamental aims of West African stakeholders (Fig. 2). Moreover, many environmental applications of MCDA use too many objectives (Marttunen et al., 2018). This is ineffective and burdens MCDA weight elicitation. We excluded some objectives in plenary discussions.

We could not assume that all participants had sufficient technical knowledge to ***create FEWS configurations***, but aimed to avoid "myopic problem representation" (Montibeller and von Winterfeldt, 2015). The Strategy Generation Table is especially suitable (Gregory et al., 2012b;Howard, 1988). It allows pre-structuring while stimulating creative stakeholder inputs. The ***context-based principle*** of co-production includes asking for constraining factors (Norstrom et al., 2020): when creating FEWS, the necessity of considering the West African situation became evident, including power cuts and slow internet. Moreover, we realized that stakeholders had not created all potentially interesting FEWS configurations. An advantage of Multi-Attribute Value Theory is that options can be included later (Reichert et al., 2015;Eisenführ et al., 2010). The FANFAR consortium created additional FEWS covering technical aspects, e.g., ensemble meteorological forecasts, redelineation and calibration of hydrological models, and assimilation of EO and in situ water levels (FEWS *h* to *k*, Table 1; Table SI-6). During post-processing, we also created the FEWS at project start, *a. Status quo*, as benchmark. Indeed, it performed poorly for most groups (Fig. 5). As summary, the three MCDA steps of stakeholder analysis, creating objectives, and FEWS took up large parts of the first workshop. They were very helpful for stakeholders to exchange ideas, express their needs, and ***develop a common understanding***, contributing to co-design step 1 (Table 4).

Table 4. Summary of MCDA process using conceptual framework for transdisciplinary research (Table 3): (1) co-design, (2) co-production, and (3) co-dissemination of knowledge. Symbols: +++ strength of MCDA; ++ well possible with MCDA; + possible contribution by MCDA; 0 not achievable by MCDA; * remark. PSM: Problem Structuring Methods; VFT: Value Focused Thinking.

ID	Step	MCDA	Remarks and recommendations
1	**Co-design**	**Joint problem framing**	
1a	Collaborative research team	0	• Include local partners in consortium (knowledge brokers, bridging organizations)
		0	• Build alliances with regional partners, also for follow-up projects (trust building)
		+++	• MCDA PSM: stakeholder analysis with simple questionnaires (sect. 3.1.2)
1b	Research questions, methodological framework	++	• MCDA can help jointly defining research questions if PSM is used
		0	• MCDA is less suitable to define project success criteria (but PSM could be used)
		+++	• MCDA provides an integrative methodological framework (sect. 3.1)
		++	• MCDA PSM: use VFT for defining shared objectives at lower level (sect. 3.1.3)
		++	• MCDA PSM: use creativity techniques to find diverse, locally adapted solutions (e.g., Strategy Generation Table; sect. 3.1.4); increases common understanding
1c	Boundary object	+	• MCDA PSM could potentially be used for creating boundary object
2	**Co-production**	**Conducting integrated research to produce new knowledge; continuous exchange**	
2a	Integrative methods	+++	• MCDA is a methodologically consistent integrative procedure, but there are others

2b	Interdisciplinary collaboration	+++	• MCDA can integrate qualitative and quantitative scientific evidence from different disciplines using predictions (sect. 3.1.5) and value functions (sect. 3.1.6)
			* Not emphasized in reviewed transdisciplinary literature: merits future research
	Uncertainty	+++	• MCDA can explicitly consider various types of uncertainty (sect. 5.1.2)
			* High relevance for projects in the earth systems sciences; merits future research
2d	Integrate practice stakeholders	++	• MCDA can integrate diverse practice stakeholders throughout project
		0	• Iterative process to integrate practice stakeholders should be included in MCDA
		0	• MCDA cannot handle discontinuous participation, or too many participants
		+++	• MCDA provides clear results, avoiding vagueness that conceals potential conflicts
2e	Pluralistic principle/ social learning	+++	• MCDA explicitly recognizes different stakeholder interests, which are integrated in model, fostering trust and avoiding conflict by finding consensus configurations
		+++	• MCDA weight elicitation: allow for uncertainty & different stakeholder preferences
		+++	• MCDA fosters learning about decision, one's own preferences, and those of others
			* To understand growing shared understanding in a group, future research is needed
		0	• MCDA does not foster training and capacity building
3	**Co-dissemination**	**Integrate and disseminate knowledge among research and societal groups, and evaluation**	
3a	Two-dimensional integration	++	• MCDA: some discussion and revision of results (to find consensus FEWS)
		+++	• MCDA provides prescriptive knowledge (e.g., suitable FEWS configurations)
		0	• MCDA cannot review and analyze other aspects (e.g., governance mechanisms)
3b	Targeted products	0	• MCDA cannot generate target products (e.g., publications, policy briefs, maps)
		0	• MCDA cannot implement and scale up knowledge for real-world problem solving
		+	• Scientific integration, generalization, and documentation is not specific to MCDA
3c	Evaluate societal and scientific impact	+	• MCDA usually does not evaluate societal and scientific impact (but is possible)
		0	• Mid-term impacts cannot be attributed to MCDA (e.g., uptake, societal effects)
		0	• MCDA cannot capture longer-term impacts, which are anyway difficult to measure

5.2.2 Evaluating the co-production step "integrated research to produce new knowledge"

Consistent ***integrative methods*** and ***systematic procedures*** for integrating bodies of knowledge are crucial (step 2a, Table 3), but less visible in literature (Wuelser et al., 2021;Lang et al., 2012;Mauser et al., 2013). Recommendations include generating hazard maps, or sensitivity and multi-criteria assessments (i.e., MCDA). Identifying stakeholders' positions and preferred options allows involving people in creating their future (Wuelser et al., 2021). In FANFAR, MCDA clearly helped structuring the co-design process and integrating different knowledge types: expert estimates of how well each FEWS performs (sect. 4.4) and stakeholder preferences (sect. 4.5). Moreover, West African stakeholders experimented with the FEWS at each workshop, tested it in rainy seasons, and provided feedback (see Wuelser et al., 2021), which cannot be attributed to MCDA.

Transdisciplinary projects rely on ***interdisciplinary collaboration*** and integrating evidence from different disciplines (step 2b, Table 3; Jahn et al., 2012;Lemos and Morehouse, 2005;Mauser et al., 2013). Integrating qualitative data for policy and decision making, and quantitative data for models can be challenging (Lang et al., 2012). MCDA handles this by transforming attributes of different measurement units (including qualitative scales) to a common value from 0 (objective not achieved) to 1 (fully achieved), using value functions (sect. 3.1.6). In FANFAR, experts provided these estimates: West African and European hydrologists, IT specialists, and decision analysts (sect. SI-2.4.1). MCDA integrates very specific data (predictions about FEWS performance). Other evidence types also need integration in transdisciplinary projects, and other methods are available. This area merits future research, given the lack of emphasis in current literature.

"Questions of the ***uncertainty of the results***" (Mauser et al., 2013; p. 428) were emphasized by earth systems scientists for global sustainability, but scarcely addressed by others (step 2c, Table 3). We included the uncertainty of expert predictions by eliciting probability distributions for each attribute (sect. SI-2.4.1) and Monte Carlo simulation (sect. 3.1.8). Local sensitivity analyses addressed uncertainty of the model and of stakeholder preferences (sect. 5.1.2; discussed in Reichert et al., 2015). Handling uncertainty in a conceptually valid way is essential for transdisciplinary research in the earth systems science.

The importance of ***integrating practice stakeholders in iterative processes*** (step 2d, Table 3) was underlined by many (e.g., Lemos and Morehouse, 2005;Norstrom et al., 2020). Our iterative workshop series to test and improve the FEWS cannot be attributed to MCDA. Practical MCDA projects often consist of three stakeholder workshops: for problem structuring, preference elicitation, and discussing results and revising options, i.e., FEWS (Fig. 1). ***Discontinuous participation*** can be a challenge (Lang et al., 2012), and FANFAR faced changing numbers and composition of participants (sect. 3.1.1). As Lang et al. (2012), we also encountered the opposite: increasing requests over time and the challenge of ***keeping participant numbers manageable***. We integrated new participants, e.g., by presenting the FEWS and MCDA objectives at each workshop. For MCDA, discontinuous participation was unproblematic, as new participants in the second workshop accepted the objectives (Fig. 2) and FEWS (Table 1). Our participant sample was presumably sufficiently large and diverse to cover main aspects. Another challenge can be ***vague results*** using methods such as sustainability visions, which may ***conceal potential conflicts*** (Lang et al., 2012). MCDA has the strength of providing clear results, even for uncertain data (sect. 5.1.2).

The ***pluralistic principle aims at creating social learning across multiple axes*** (step 2e, Table 3). Sustained interaction with stakeholders, jointly searching for solutions, and joint learning foster ***trust***, ***mutual understanding***, and ***shared perspectives*** (e.g., Lemos and Morehouse, 2005;Norstrom et al., 2020;Schneider et al., 2019). ***Recognizing different expertise, perspectives, values, and interests*** does not require reaching consensus (e.g., Norstrom et al., 2020;Wuelser et al., 2021). However, collaboratively ***engaging with conflicts*** is needed to rationalize contested situations (Schneider et al., 2019;Caniglia et al., 2021). A strength of MCDA is that opposing stakeholder interests are part of the methodology, hereby often avoiding conflict about solutions (Arvai et al., 2001;Gregory et al., 2012a;Gregory et al., 2012b;Marttunen and Hamalainen, 2008). During weight elicitation, we encouraged stakeholders to discuss diverging preferences (sect. 3.1.6), and we recommend allowing for such uncertainty. It helps participants ***construct own preferences*** (Lichtenstein and Slovic, 2006), enables ***learning*** and ***understanding alternative perspectives***, and informs sensitivity analyses (sect. 4.7). In FANFAR, conflicting preferences did not change FEWS rankings, and we identified consensus FEWS (sect. 5.1.2). In other cases, sensitivity analyses based on diverging preferences can help construct better FEWS. "Assessing the [interactive] principle should also focus on capturing learning, how the perceptions of actors change throughout the process, and the degree to which a ***shared perspective emerges***" (Norstrom et al., 2020; p. 188). Such research is rare in MCDA, but was attempted in FANFAR and a Swiss project (Kuller et al., in prep.). Results were ambiguous, but we found shared agreement of FANFAR stakeholders about the most important objectives. More research to better understand individual cognitive and group decision making processes is needed (Kuller et al., in prep.).

Training and capacity building belong to the ***pluralistic principle*** (step 2e, Table 3). Many of 31 transdisciplinary projects provided e.g., trainings, or attractive visualizations of recent research (Schneider et al., 2019). Capacity building can be promoted by working in integrated ways discussed above, or with capacity building courses (Wuelser et al., 2021;Caniglia et al., 2021). FANFAR offered many training and capacity building opportunities, which cannot be attributed to MCDA.

5.2.3 Evaluating the co-dissemination and evaluation step "integrating and disseminating knowledge"

Two-dimensional integration (step 3a, Table 3) implies that outcomes are ***discussed and revised*** from scientific and societal perspectives (Mauser et al., 2013;Lang et al., 2012). Discussing ***transformation knowledge*** includes measures, tools, or governance mechanisms to create change (Schneider et al., 2019). It can include ***prescriptive knowledge***, recommending suitable options (Caniglia et al., 2021). This is a strength of MCDA: we provided detailed information about robust FEWS configurations (sect. 5.1). Moreover, MCDA results are discussed with stakeholders and new FEWS could be constructed (Fig. 1). We could not carry out the fourth FANFAR workshop due to COVID-19, but collected online feedback. Stakeholders were quite satisfied with the FANFAR FEWS performance during the 2020 rainy season (Fig. 7). While not meeting requirements of extensive discussions, it was the best available approach. We are currently carrying out a systematic daily reforecasting experiment covering 1991–2020 for five model configurations, and aim to link results to expert satisfaction. Understanding ***governance mechanisms*** is out of scope of MCDA; in our case, ways to facilitate uptake of the FEWS across entire West Africa.

Target products (step 3b, Table 3) should address the original problem, be understandable, and accessible to users (Lemos and Morehouse, 2005;Schneider et al., 2019;Lang et al., 2012). Products include technical publications, data visualizations, and open access online databases (Schneider et al., 2019). In FANFAR, products cannot be attributed to MCDA. Main product is the FEWS (including operational data collection, assimilation, hydrological modelling, interpretation, and distribution through web visualization and API), where MCDA only supported the design. Additional products are a multilingual knowledge base (https://fanfar.eu/support/), open source code (https://github.com/hydrology-tep/fanfar-forecast), and video tutorials (www.youtube.com, search: HYPEweb FANFAR). Assuring ***consistent access, maintenance, updates, and improvements***

after project termination is challenging (Lemos and Morehouse, 2005). AGRHYMET has the authority to drive the FEWS uptake and already uses it, e.g., in their MSc curriculum, or at PRESASS and PRESAGG forums (WMO, 2021), supporting the ECOWAS flood management strategy. Nevertheless, operationalization after EU financing is not secured.

Products should contribute to scientific progress, a major challenge being inadequate ***generalization of case study solutions*** (Lang et al., 2012;Jahn et al., 2012). Products are often not reported in scholarly literature (Wuelser et al., 2021), the knowledge thus not advancing scientific progress, and not being adopted in similar projects. We aimed to overcome this with this paper and other outputs (FANFAR, 2021). We document the MCDA process, providing details in the Supplementary Information. We encourage hydrologists to use this material. We stress that it is not necessary to conduct a full MCDA in every case. The first problem structuring steps can create useful insights, and may be easier to apply (sect. 5.2.1).

The last step 3c (Table 3) is to ***evaluate societal and scientific impact***. Project evaluation is possible with MCDA, but MCDA was not used in FANFAR. Short-term impacts include ***increased citations or attention of nonacademic actors***, e.g., high download rates, or media coverage (Norstrom et al., 2020;Schneider et al., 2019). As example, the FANFAR workshop in Nigeria featured on the national TV news. ***Building social capacities and establishing stakeholder networks or communities of practice*** can be very helpful (Lemos and Morehouse, 2005;Schneider et al., 2019). A FANFAR social media group among West African stakeholders monitored the severe 2020 floods, which in many places were successfully forecasted by the FANFAR FEWS. Mid-term impact includes ***uptake of products*** and societal effects such as ***strategy implementation, or amended legislation*** (Jahn et al., 2012;Norstrom et al., 2020). ***Long-term impacts*** are very difficult to measure as they are typically realized far beyond project termination (Norstrom et al., 2020;Schneider et al., 2019). Moreover, due to the complexity of problems in transdisciplinary projects, causal relationships are difficult to establish (Lang et al., 2012). To secure future sustainability of the FANFAR FEWS, a set of dialogues with potential financiers were held, and 12 proposals were submitted to date. Four were successful so far, providing funding for some parts of FANFAR (e.g. hydrometric stations by AfDB, additional training by Sida and EDF via ECOWAS). The sustainability strategy focuses on financing (of operations, maintenance, dissemination, technical development, etc.) and importantly on long-term collaboration, capacity development, transfer of responsibilities, and on anchoring FANFAR in the routines of West African institutions. As one example of ***societal impact***, NIHSA (Nigeria Hydrological Services Agency) reported that an early FEWS warning in September 2020 saved approximately 2’500 lives. The warning helped evacuating five communities before the flood destroyed more than 200 houses.

6 Conclusions

The MCDA process enabled finding three good FANFAR FEWS configurations, which is important to West African stakeholders and people affected by floods. All stakeholder groups preferred a relatively simple FEWS producing accurate, clear, and accessible flood risk information that reaches recipients well before floods. To achieve this, most groups would trade-off higher operation and maintenance costs, development time, and several languages. MCDA indicated that the three FEWS are robust. They achieved 63–70% of all 10 objectives despite diverging stakeholder preferences, model uncertainty, and uncertain expert predictions. Including uncertainty and stakeholders in MCDA is neglected in flood risk research. We highly recommend both: MCDA including uncertainty allowed better distinguishing between FEWS, and participatory MCDA focusing on stakeholders' objectives (Value Focused Thinking), helped avoid conflicts about FEWS configurations. Hopefully, participatory MCDA increased trust and capacity building among West African stakeholders, thus enabling future uptake of the FEWS.

MCDA meets many, but not all requirements of sustainability science and transdisciplinary research. Our proposed evaluation framework proved very useful for critically analyzing MCDA. We invite others to apply it for guiding their projects, and to evaluate our framework. It includes elements underrepresented in literature but crucial to the earth systems sciences: uncertainty and integrating interdisciplinary knowledge. We evaluated MCDA as a transdisciplinary process along the three framework steps. MCDA only partially contributes to co-design (step 1). However, if understood as a process including problem structuring, MCDA supports joint problem framing. Stakeholder analysis helps identifying those to involve. Problem structuring includes creativity techniques for defining shared objectives and designing options (i.e., FEWS configurations). The main benefit of participatory MCDA lies in co-production (step 2). Interdisciplinary knowledge integration and uncertainty were rarely emphasized in literature and could be research contributions to the earth systems sciences. Both are strengths of MCDA. MCDA also provides clear results and consensus FEWS by integrating conflicting stakeholder interests into the model. MCDA does not well achieve many aspects of co-dissemination (step 3). MCDA results are discussed with stakeholders, but this focus is narrow. MCDA does not achieve important elements such as analyzing governance mechanisms, and implementing actions and products. In FANFAR, we thus carried out complementary activities.

As many others, we believe that transdisciplinary research contributes to solving our global problems, and can advance scientific progress. We hope that this paper documents and helps to better understand a transdisciplinary process in a complex setting: producing a good FEWS for West Africa, together with many stakeholders. We contribute to literature by analyzing the strengths and limits of a comprehensive, participatory MCDA process for such endeavors. We encourage our colleagues from the earth system sciences to engage in transdisciplinary research with stakeholders and society.

7 Data availability

The data will be available on the Eawag Research Data Institutional Collection (ERIC: https://opendata.eawag.ch), DOI: xxx

8 Supplement link

In the Supplementary Information (SI), we provide ample material to guide readers unfamiliar with Multi-Criteria Decision Analysis (MCDA) through all steps. This includes a Methods section (generating FEWS configurations, eliciting weights, MCDA model, sensitivity analyses, stakeholder feedback), and a Results section (stakeholder analysis, objectives and attributes, FEWS, predictions, value functions, weights, MCDA results, and stakeholder feedback).

9 Author contribution

Judit Lienert: Conceptualization, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, writing – original draft preparation, rewriting, revisions. Jafet Andersson: Funding acquisition, investigation, project administration, writing – review & editing. Daniel Hofmann: Data curation, formal analysis, visualization, validation, writing – original draft preparation. Francisco Silva Pinto: Formal analysis, investigation, methodology, project administration, writing – review & editing. Martijn Kuller: Investigation, project administration, supervision, writing – review & editing.

10 Competing interests

The authors declare that they have no conflict of interest.

11 Special issue statement

This paper was prepared for the special issue: "Contributions of transdisciplinary approaches to hydrology and water resources management".

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