Impact-based flood early warning for rural livelihoods in Uganda

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ABSTRACT: Anticipatory actions are increasingly being taken before an extreme flood event to reduce the impacts on lives and livelihoods. Local contextualized information is required to support real-time local decisions on where and when to act and what anticipatory actions to take. This study defines an impact-based, early-warning trigger system that integrates flood forecasts with livelihood information, such as crop calendars, to target anticipatory actions better. We demonstrate the application of this trigger system using a flood case study from the Katakwi District in Uganda. First, we integrate information on the local crop cycles with the flood forecasts to define the impact-based trigger system. Second, we verify the impact-based system using historical flood impact information and then compare it with the existing hazard-based system in the context of humanitarian decisions. Study findings show that the impact-based trigger system has an improved probability of flood detection compared with the hazard-based system. There are fewer missed events in the impact-based system, while the trigger dates are similar in both systems. In a humanitarian context, the two systems trigger anticipatory actions at the same time. However, the impact-based trigger system can be further investigated in a different context (e.g., for livelihood protection) to assess the value of the local information. The impact-based system could also be a valuable tool to validate the existing hazard-based system, which builds more confidence in its use in informing anticipatory actions. The study findings, therefore, should open avenues for further dialogue on what the impact-based trigger system could mean within the broader forecast-based action landscape toward building the resilience of at-risk communities.

KEYWORDS: Adaptation; Community; Decision-making; Emergency preparedness; Flood events

1. Introduction

Disasters associated with weather extremes are affecting the lives and livelihoods of millions of people across the world. In 2020, floods were the most common type of disaster, with a 23% increase in events from 2000 to 2019. In 2020 in Africa, floods affected more than 7 million people—the most since 2006 (Centre for Research on the Epidemiology of Disasters 2021). In Uganda, floods affected approximately 800 000 people across 64 districts in 2020 (Directorate-General for European Civil Protection and Humanitarian Aid Operations 2020). Rural vulnerable communities are most at risk due to low coping capacity and lack of localized, tailor-made, early-warning information (Naab et al. 2019). Timely and actionable information should be available to rural at-risk communities, and dialogue about appropriate coping strategies involving these communities improved. To support this, humanitarian actors and disaster-management agencies require local, contextualized information about the hazard and likely impacts on at-risk communities to guide more targeted interventions.

Early-warning information (EWI), therefore, can play a key role in risk reduction and management of flood risks (Thiemig et al. 2011; Okonya and Kroschel 2013). Notably, frameworks such as the Sendai Framework for Disaster Risk Reduction highlight the need to disseminate EWI to support the shift from response to anticipatory actions and to mitigate the risks of extreme events for at-risk communities (United Nations 2015). The development of flood early-warning systems has advanced significantly over the past decade (Pappenberger et al. 2008; Cloke and Pappenberger 2009; Hallegatte 2012; Dale et al. 2014). However, a gap still exists in ensuring that EWIs are used effectively to activate early flood interventions, especially at the local level (Baudoin et al. 2016; Cools et al. 2016). This is because most hazard-based EWIs describe the physical characteristics of the event with little or no information on the likely impacts of the expected extreme event, which can limit the design of the required interventions if a hazard or damage curve is not previously established. For example, in Uganda, there were difficulties in using the forecast information to define the magnitude and danger thresholds that would result in significant impacts (Coughlan de Perez et al. 2016).

Impact-based forecasting (IbF) ensures that EWI is linked to the expected consequences (impacts) on the population and their livelihoods to understand where, when, and what specific anticipatory actions are needed (WMO 2015). In addition, the provision of impact-based information can significantly influence risk perception among the users and decision-makers (Potter

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et al. 2018; Weyrich et al. 2018; Potter et al. 2021). However, the development of impact-based forecast information requires a people-centered approach supported by multistakeholder collaborations and driven by at-risk communities (Baudoin et al. 2016; Sai et al. 2018; Klassen and Oxley 2021).

Several approaches can be used for impact-based forecasting (Wilkinson et al. 2018), with the common ones being impact-based modeling (Hemingway and Robbins 2020) and an impact-oriented approach (Kaltenberger et al. 2020). The impact-based modeling includes complex quantitative impact models overlaying hazard, vulnerability, and exposure. On the other hand, the impact-oriented approach can be based on subjective or objective criteria, for example, by subjectively discussing the likely impacts of a flood event with stakeholders (Kaltenberger et al. 2020) or setting variable trigger thresholds and targeted early actions through stakeholder consultations. The method adopted will depend on the hazard context, available data, information to build the hazard-risk knowledge (Potter et al. 2021; Wagenaar et al. 2017), available historical impact information to set up danger thresholds (Harrison et al. 2022),the validation of the impact models (Dottori et al. 2017), as well as the intended user or user groups of the impact-based information (WMO 2015).

In the least developed countries, IbF based on a quantitative, impact-based modeling approach has been hindered by scarce risk and impact information. Such information is required to build a link among hazard, vulnerability, exposure, and impacts (Wilkinson et al. 2018) and to validate the impacts of different levels of forecast warnings (Mitheu et al. 2023). Nevertheless, each situation would require a specific approach that meets the remits of the users. For example, at-risk communities could benefit more from an impact-oriented approach (Kaltenberger et al. 2020), which uses available, historical flood impact information to define the danger levels at which flooding occurs. For example, available impact information from data repositories such as DesInventar [United Nations International Strategy for Disaster Reduction Secretariat (UNISDR) 2018] and the Emergency Events Database (EM-DAT; Centre for Research on the Epidemiology of Disasters 2020) can be integrated with local information gathered from community engagement (Tarchiani et al. 2020) to provide more localized risk information. The local information is useful in ensuring IbF systems are more dynamic regarding the danger levels and are valuable in triggering targeted anticipatory actions. Depending on the context, local information, in addition to information about built-up area, infrastructure, and inhabitants, could include the seasonal crop calendar, livestock sale schedules, market functionalities, and household economy analysis (Seaman et al. 2014). For example, during the 2020 monsoon floods in Bangladesh, the seasonal rice calendar helped the Food and Agriculture Organization of the United Nations (FAO) intervene just before the sowing season to protect rice seeds for the most vulnerable communities by providing watertight storage kits (FAO 2021).

"Livelihood" is defined as how people make a living, which comprises capabilities, assets, and activities required to secure life necessities, including food and nonfood items (Chambers 1995; Scoones 1999; Boudreau et al. 2008). In East Africa, anticipatory actions toward livelihood protection and food insecurity crises, such as reduced crop yields and livestock losses, are often focused on slow-onset disasters such as drought (World Food Program 2021). However, floods due to heavy rainfall and waterlogging also lead to devastating losses of crops and livestock. For example, in the Katakwi District of Uganda, more than 65 000 acres (1 acre = 0.4 ha) of main crops (e.g., beans, groundnuts, green grams, potatoes) were destroyed during the April to June 2018 rainy season (UNISDR 2018). These agriculture-based livelihoods are mainly rain-fed and support approximately 80% of Uganda's rural population. Therefore, there is a need to consider people's livelihood sources and coping strategies when developing IbF systems so that at-risk rural communities can better protect their livelihoods and develop coping practices better adapted to changing weather patterns.

In Uganda, due to the current lack of a local flood-forecasting system (Atyang 2014), forecast information from the Global Flood Awareness System (GloFAS) has been used to inform early warnings and anticipatory actions through the development of a hazard-based flood early-warning trigger system (HbFEWtS; Uganda Red Cross Society 2021). GloFAS provides freely available flood hazard forecasts under the funding from European Commission's Copernicus Emergency Management Service (Alfieri et al. 2013). Our study aims to refine the existing HbFEWtS by integrating crop cycles and crop-impact information to explore variable triggering thresholds and targeted anticipatory actions. The objectives of the study are to 1) gather the livelihood data from the local communities, 2) develop the impact-based component and integrate it with the forecasts to define an impact-based flood early-warning trigger system (IbFEWtS) using the impact-oriented approach proposed by Kaltenberger et al. (2020), and 3) evaluate the two systems using historical flood impacts information in the context of humanitarian actions (i.e., actions that are triggered based on the likelihood of high-magnitude floods and the available resources) by the Uganda Red Cross Society (URCS). In this study, we use the term "impact data/information" to refer to quantitative and qualitative information reported on the type of impacts on lives, livelihoods, and infrastructure derived from global data repositories (namely, DesInventar and EM-DAT).

In the following subsections, we describe the HbFEWtS already in use by URCS, highlight the data collected at the local level, and define the IbFEWtS that integrates forecasts and crop impact information based on the livelihoods impact-based flood forecasting (LIMB) framework (Ciampi et al. 2021) developed under the Science for Humanitarian Emergencies and Resilience (SHEAR) National-Scale Impact-Based Forecasting of Flood Risk in Uganda (NIMFRU)[1] project. The IbFEWtS and the HbFEWtS are then compared through a case study based in the Katakwi District, and the following research questions are addressed: 1) How do the skill (as measured by statistical skill scores) and the thresholds of the two trigger systems compare for humanitarian actions?

[1] NIMFRU is cofunded by the U.K. Foreign, Commonwealth, and Development Office and the U.K. Natural Research and Environment Council (https://walker.reading.ac.uk/project/nimfru/).

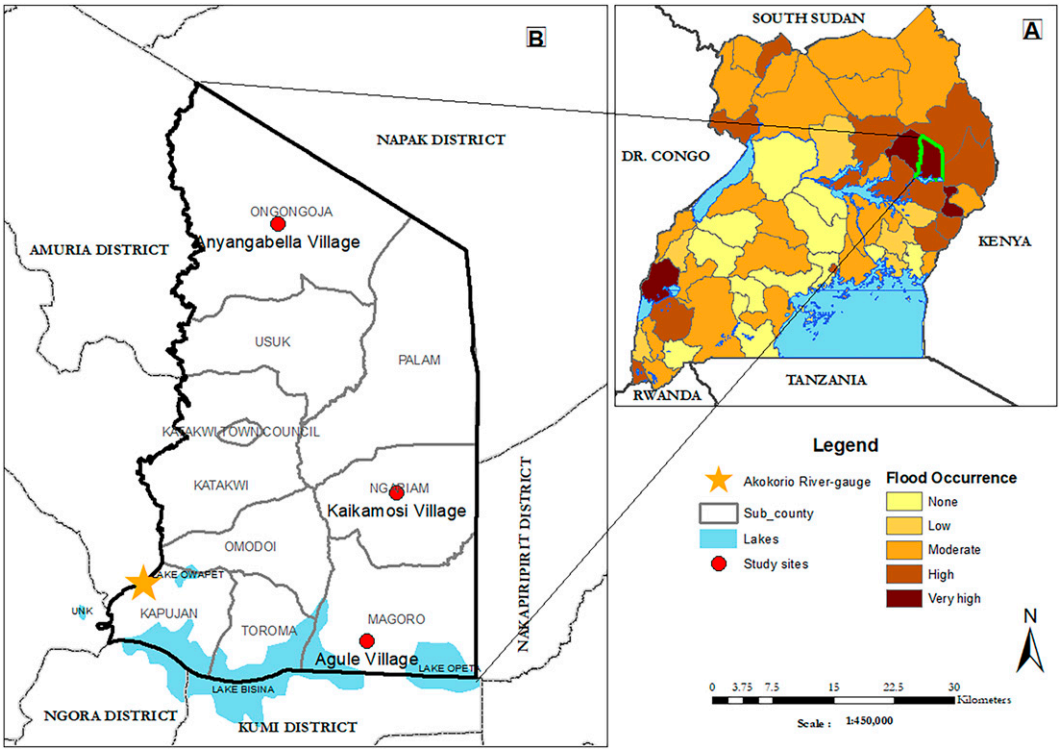

FIG. 1. (a) Map of Uganda showing flood occurrence, where Katakwi is ranked among the priority districts because of the high occurrence of floods. (b) The zoomed inset of the Akokorio River gauge location and the study villages within the Katakwi District where local information on flood impacts and crop calendars was collected.

2) Does the impact-based flood early-warning trigger system change how anticipatory actions are targeted?

2. Materials and methods

a. Case study

The URCS is currently implementing the Early Action Protocol (EAP) for floods in flood-prone districts under the IKEA Foundation's Innovative Approaches for Response Preparedness (IARP) project. An EAP refers to a pre–agreed-upon set of procedures and mechanisms that allow humanitarian organizations, governments, and other stakeholders to respond to disasters quickly and effectively to reduce the impact of the disaster and save lives. One of the flood-prone districts is Katakwi, which the NIMFRU stakeholders also selected (Mitheu et al. 2022). Katakwi suffers from waterlogging and seasonal flooding and is among the districts that have experienced the highest flood events from 2007 to 2018 (Fig. 1a). The district comprises two livelihood zones: crop and livestock and fishing and livestock. The crop and livestock zone covers Ongongoja, Ngariam, and parts of Magoro subcounties, while the fishing and livestock zone covers areas around Lakes Opeta and Bisina in Opeta parish (Fig. 1b). The Katakwi District is selected to develop the IbFEWtS as a proof of concept by integrating crop-impact information collected from three purposively selected villages (Fig. 1b) with flood forecast information from GloFAS.

b. The hazard-based flood early-warning trigger system for Uganda

The current HbFEWtS uses a predefined trigger threshold derived from discharge probability to define the danger threshold when anticipatory action(s) should be taken (Coughlan de Perez et al. 2016; Wilkinson et al. 2018). These systems ensure that decisions about triggers, actions, and targeting are made well in advance and implemented through an EAP whenever the set criteria are met (International Federation of Red Cross and Red Crescent Societies 2020a). Anticipatory actions can be triggered if a predefined threshold representing an impactful flood is reached. This threshold is obtained from observational data, historical river flow forecasts, or rainfall observations.

Setting up a hazard-based early-warning system for a particular hazard begins by identifying the areas at risk and the priority impacts that would require anticipatory actions. Forecast information that meets the preferences of the stakeholders is then chosen based on availability. A wide range of forecast information can be used. The forecast information should be evaluated before being used in the hazard-based system, to minimize the chances of taking actions that are not followed by an extreme event. Forecast skill assessment is, therefore, important in designing these robust systems. Based on stakeholders' preferences, the current HbFEWtS for Uganda uses forecast information from GloFAS, version 3.1 (v3.1). For example, when GloFAS indicates a 60%–70%

chance of a 5-yr return-period flood at a 5-day lead time (LT), pre-agreed actions will be triggered through the EAP (URCS 2021). This forecast information has been evaluated as skillful using river-gauge observations collected across Uganda (A. Ficchi et al. 2021, unpublished manuscript; Mitheu et al. 2023). Mitheu et al. (2023) provide a full description of GloFAS v3.1.

c. Data collection

Data collection was organized as part of NIMFRU project and included researchers from Uganda and international institutions. Data collection fieldwork took place from February 2019 to February 2020, when qualitative and quantitative data were collected from three village sites in Katakwi District. The initial process started with the development of use cases targeting at-risk communities in the selected sites. Mitheu et al. (2022) provide a comprehensive description of the use cases. Quantitative data were collected using the household economic assessment methods (Seaman et al. 2014), which included assessing the various livelihood components (e.g., livelihood type, source of income, assets owned, expenditure, off-farm activities) at the household level. Qualitative data including coping practices, barriers to coping, response to flood hazards, as well as impacts on crops were collected through the Farmers' Agri-Met Village Advisory Clinics (FAMVACs), codesigned during the NIMFRU project with the Uganda National Meteorological Authority (UNMA). The FAMVAC method was complemented by semistructured one-on-one interviews. Ciampi et al. (2019) and Mitheu et al. (2022) provide a comprehensive description of the FAMVACs approach and the qualitative data collection methods, respectively.

Among the qualitative data collected from village sites, data on the crop types and dates or months when various crops were affected by floods were used to inform this study. These data were integrated with crop calendars for Uganda retrieved from the Famine Early Warning System Network (FEWS NET; FEWS NET 2013) and combined with the NIMFRU crop calendars drawn up by the household economy assessment (HEA) researchers as part of the NIMFRU baseline study (Petty et al. 2021). This calendar reflects the timing for the different crop cycles in an agricultural year. The combined crops calendars and the timing of the impacts on the various crops were used to develop crop impact matrices for the three villages to inform the impact-based trigger system. The historical flood impact information for Katakwi derived from DesInventar and EM-DAT from 2007 to 2018 was then used to evaluate the two trigger systems using the probability of detection (POD) and false alarm ratio (FAR) skill scores (Wilks 2006). Mitheu et al. (2023) provide a detailed description of these global data repositories for Uganda. Table 1 shows the type of flood impacts reported, their timing, and the magnitude of the flooding during that period. The flood magnitudes were extracted from the GloFAS v3.1 for the Akokorio River gauge station. All other data as described above that were not used in this paper will be published separately to inform the aim of the NIMFRU project.

d. The impact-based flood early-warning trigger system

For wider applicability in informing sectoral-based decisions (e.g., in agriculture, livestock, health), we defined an impact-based trigger system that integrates forecasts with local information through an impact-oriented approach (Kaltenberger et al. 2020). We then refined the system with information on crop cycles and flood impacts from the Katakwi District. Here, we assess how the crop cycles help identify critical times when floods affect crops and how targeted interventions can be designed to ensure reduced risks. The components of the IbFEWtS are elaborated further below and.

The components of the IbFEWtS are summarized in Fig. 2. In addition, the principal components of existing HbFEWtS (e.g., the one followed for the Uganda EAP for floods) are retained (components 1–3). Within each component, the grid box represents spatial variability (e.g., different districts or counties in Uganda at a given time). The retained components are summarized as follows:

1) A risk analysis combines flood hazard, exposure, and vulnerability layers to delineate areas at risk of flooding. Based on location and context, this component can also represent the risks and vulnerability of any other hazard, such as drought and tropical cyclone.
2) Hydrometeorological forecasts (considering forecast skill) derive trigger thresholds based on stakeholders' preferences and consider the risk profiles. The distribution of threshold exceedances shows areas likely to report a high risk of impacts (for this case, a high probability of flooding with significant exposure and vulnerability).
3) The threshold exceedances show areas that will require triggering early actions. Conversely, no actions will be triggered if the forecast threshold is below the predefined threshold.

The additional components needed for the IbFEWtS include the following:

4) The integration of crop cycles with forecasts for each administrative area. Based on the context, this component can consist of other local information (e.g., livestock sale schedules, socioeconomic variables).
5) A variable trigger threshold can be adapted to ensure differential triggering that better reflects more critical times of the cropping year. For example, the trigger threshold is lowered (right-hand-side squares in Fig. 2) during the harvesting and the start of the second planting season. Historical flood impact information is used to evaluate the trigger systems (both hazard and impact based) according to the set criteria and selected skill scores.
6) A range of anticipatory actions is derived through stakeholders' consultations reflecting agricultural management practice at specific times of the year. For example, actions during the harvesting season are likely to be different from those during the planting season.

3. Results

In this section, we describe the crop-impact information collected from the local communities in Katakwi and

TABLE 1. Flood timelines for Katakwi based on historical flood impact information from DesInventar and EM-DAT repositories. For the years between 2007 and 2018 that are omitted in this table, no impact information was available.

Flood timelines based on historical impact information				GloFAS v3.1 (5 days LT)	
Flood year	Flood month(s)	Flood impacts	Data collectors/ provider	Highest flood magnitude	Description
2007	Jul–Oct	Thousands of people were affected, homes were damaged, and crops were destroyed; a total of 29 000 households were affected in the six districts	URCS; Office of Prime Minister (OPM)	10-yr RP	The highest magnitude of above 10-yr RP was reached in Jul, Aug (3 yr), and Sep (5 yr)
2008	Nov	About 6000 people were affected by floods	New Vision	95th percentile	Flows were above the 95th percentile on 12 Nov
2010	Apr, May, and Sep	In April, flooding affected 7000 people in four subcounties, and roads were affected; in May, waterlogging resulted in the rotting of crops such as cassava, with about 240 gardens destroyed in various villages; in September, water from neighboring districts affected infrastructure, crops, and grazing lands and more than 3500 ha of crops were lost	Chief Administrative Office (CAO)—Katakwi; OPM; New Vision	1.5-yr RP	Peak flow of above 1.5-yr RP in mid-May; in Sep, flows were above the 90th percentile
2011	Sep–Nov	Thousands of people were affected, and crops were destroyed in Aketa and Obulengorok in Ongongoja	URCS; New Vision	3-yr RP	Peak flow of 3 yr in Sep
2012	Aug–Sep	Crops such as cassava and sorghum were destroyed, roads were unpassable, houses and latrines were damaged, and crops rotted; water sources were contaminated; more than 10 000 acres of crops were submerged	CAO; OPM	10-yr RP	Flows were above the 95th percentile, with a peak above 10 yr at the end of Jul and 3 yr in Aug
2013	Oct	Planted crops started rotting in several villages of Acuru, Abwokodia, Otujai, and Adurukai	OPM	3-yr RP	Flows with a peak of above 3 yr RP occurred in Aug
2014	Oct	Crops in the subcounties of Omodoi, Usuk, and Ongongoja were destroyed	CAO—Katakwi	2-yr RP	Flows above 2 yr RP in Sep
2017	Sep	Crops were destroyed, including 210 acres of millet	District files; CAO	2-yr RP	Flows peaked at a 2 yr RP in mid-Aug
2018	Apr–Jun	Major crops (beans, groundnuts, potatoes, and green grains) were destroyed, 65 403 acres of crops were destroyed, and houses and schools were damaged	District files; New Vision; interviews	10-yr RP	Flows were above 95th percentile from Apr with a peak above 10 yr in May; late-Jun 2-yr flows

demonstrate how the IbFEWtS could be deployed in a local context based on flood forecasts and this local information.

a. Local impact data from village sites in the Katakwi District

The crop calendar developed by NIMFRU project (Petty et al. 2021), in combination with the crop calendar developed be FEWS NET and information on collected from village sites in Katakwi on flood impact on crops, was used to develop crop impact matrices for each village (Fig. 3). These matrices show that most major crops are negatively affected by floods and waterlogging from July to November, with slight variations across the villages. For example, significant adverse impacts occurred from July to October in Anyangabella village, from August to November in Kaikamosing, and from August to October in Agule village. Major crops affected include cassava, sweet potatoes, groundnuts, sorghum, green grams, cowpeas, millet, and maize. On the other hand, positive impacts are noted during the

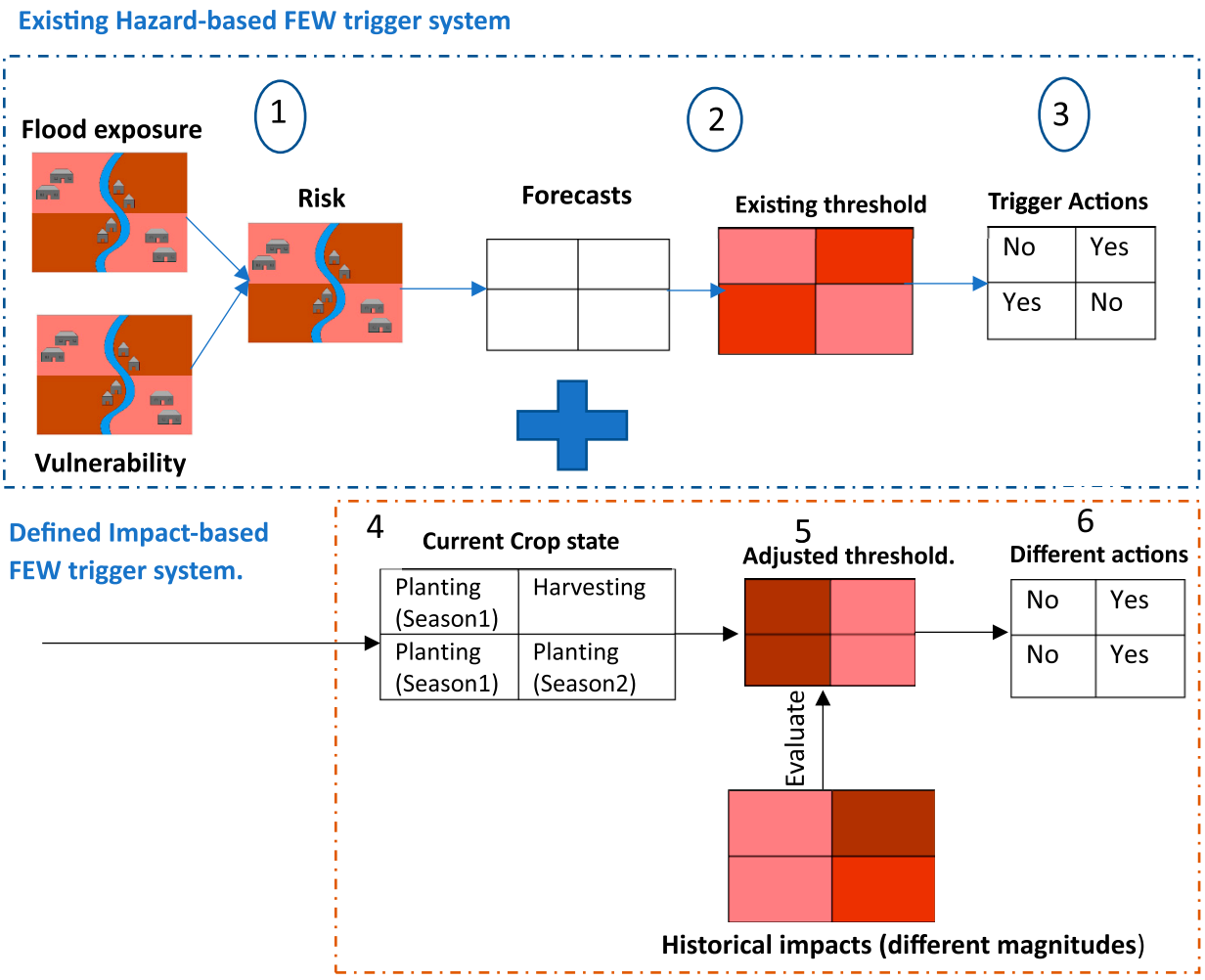

FIG. 2. The IbFEWtS that integrates local information developed on the basis of concepts from Boult et al. (2022). Numbers 1–3 represent the existing components of the HbFEWtS. Numbers 4–6 represent the new local dynamic IbF components. Grid boxes (matrices) represent spatially varying values (from dark brown for high values to light brown for low values) of vulnerability, exposure, risk, and impacts. Colors in component 2 represent varying trigger threshold values (dark brown indicates that the predefined trigger was reached, and light brown indicates that it was not reached). Component 5 represents adjusted thresholds on the basis of local information (dark brown indicates that the threshold was adjusted upward, with no triggering; light brown indicates that the threshold was adjusted downward to ensure triggering).

same period, especially for fruit trees such as lemon, orange, mango, and jackfruit, across all village sites (see Fig. A1 in the appendix) and for bananas and rice in Kaikamosing and Agule villages but not in Anyangabella village. Livestock is also negatively affected by floods across the three villages during the two rainy seasons. The negative impacts on crops are mostly experienced during the harvesting (June–August) and second planting season (September–November), as seen from the crop calendar (Fig. 3). For this study, we have indicated distinct periods for the harvesting and planting seasons in Fig. 3 based on the generic calendar that combines all crops and was derived from FEWS NET. We note, however, that specific major crops may have overlaps between the harvesting and second planting season where, for most crops, the harvesting season may be extended up to December (FAO 2022). The information on crop impacts has been integrated with GloFAS v3.1 flood forecasts to define the IbFEWtS for Katakwi, as elaborated further next.

b. *The impact-based flood early-warning trigger system for Katakwi*

Forecast information from GloFAS v3.1 at the Akokorio gauging station is integrated with the crop cycles for Katakwi within the defined IbFEWtS (Fig. 2) to develop the IbFEWtS for the Katakwi District. This system considers floods at five days LT at 60%–70% forecast probability (FP) and a varied threshold based on the crop cycles. For this case, we have adopted different thresholds for the first planting season (March–May), second planting season (September–November), and the harvesting season (June–August) based on initial

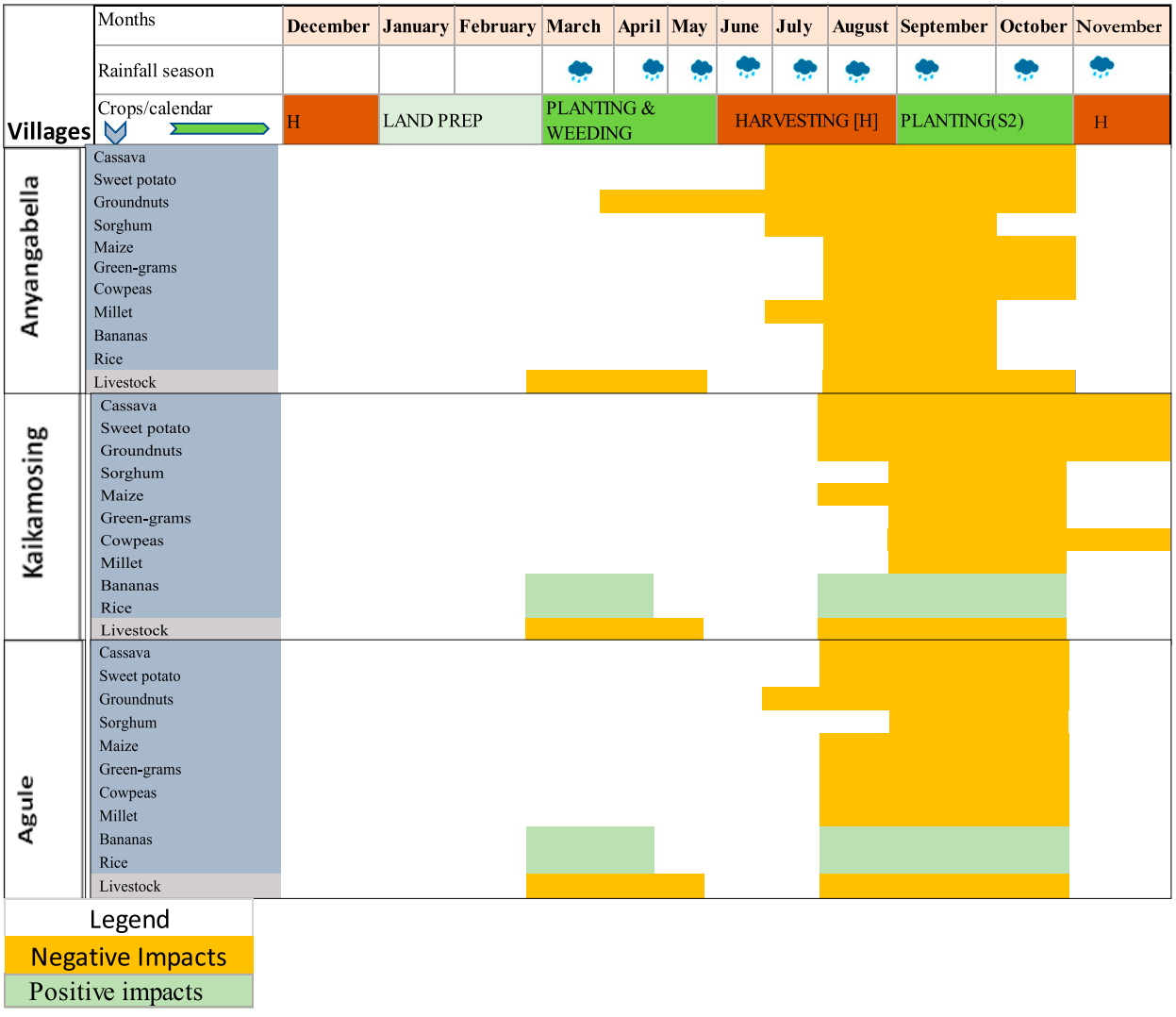

FIG. 3. Crops, crop calendar, and flood/waterlogging impact matrices for the three village sites in the Katakwi District.

reports on flood impacts on crops collected from the communities (Fig. 3) and the need to minimize the trigger frequency. Based on this information, a threshold of 10-yr return period (RP) has been adopted for the first planting season, which is noted as a noncritical period when minimal impacts are likely to occur. On the other hand, the harvesting period has been cited as the most critical when high impacts are likely to occur; hence, a threshold of a 3-yr RP has been assigned. And the second planting season has been noted as moderately critical since it overlaps with the harvesting period for most crops; hence, a threshold of 5-yr RP has been assigned. The choice of the varied thresholds used here is based on 1-yr impact data from farmers (Fig. 3); hence, they can be subjective. In addition, actions cannot be retriggered within a period equivalent to the action's lifetime. Here, the action lifetime is defined as the period in which anticipatory action will still have positive impacts (see Coughlan de Perez et al. 2016). For this study, which is based on a crop calendar, we have considered an action lifetime of 30 days.

The historical flood impacts information (Table 1) is then used to evaluate both the hazard-based and the impact-based systems. The two systems are presented in Fig. 4. Because of the lack of complete flood impact information for the Katakwi District before 2007, only 12 years have been considered in this study. The exact dates when anticipatory actions could have been triggered for the two systems are shown in Table 2. The outputs from these systems have been used to address several questions in the following sections.

c. *How do the skill and the trigger thresholds of the two systems compare?*

From Fig. 4, we can assess the skill of the two trigger systems in detecting flood events using historical flood impact information (Table 1). A contingency table is developed, shown in Fig. 5, and is used to compute the POD and FAR.

	Months / Years	March	April	May	June	July	August	September	October	November
Hazard-based trigger model	GloFAS reforecasts ENS v3.1 at 90th percentile-ref observed Q (60-70% probability, 5days LT). Predfined threshold-5 Years RP									
A	2007					Yes		Yes		
	2008									
	2009									
	2010									
	2011									
	2012					Yes				
	2013									
	2014									
	2015									
	2016									
	2017									
	2018			Yes						
Impact-based trigger model	GloFAS reforecasts ENS v3.1 integrated with crop cycles. Magnitudes derived from GloFAS(60-70% FP),5days LT									
	Crop cycle	P(S1)			Harvesting			P(S2)		
B	Threshold	10years			3years			5years		
	2007	<1yr			<1yr	10yr	3yr	5yr	<1yr	
	2008	<1yr			<1yr			<1yr		
	2009	<1yr			<1yr			<1yr		
	2010	<1yr		1.5yr	<1yr			<1yr		
	2011	<1yr			<1yr	1.5yr		3yr	<1yr	
	2012	<1yr			1.5yr	10yr	3yr	<1yr		
	2013	<1yr		2yr	<1yr		3yr/<60FP	<1yr		
	2014	<1yr			<1yr			2yr	<1yr	
	2015	<1yr			1.5yr	<1yr		<1yr		
	2016	<1yr								
	2017	<1yr					2yr	<1yr		
	2018	<1yr	2yr	10yr	2yr	<1yr	<1yr			

Year-yr
Harvesting [H]
Planting season 1-P(S1)
Planting season 2-P(S2)
Triggers

FIG. 4. (a) The existing HbFEWtS. (b) The IbFEWtS for the Katakwi District. The impact-based trigger system integrates local information on crop cycles with forecasts. Flood RPs have been extracted from GloFAS v3.1. The crop cycle reflects the actual stage of crops when floods occur. The triggers represent the time/month when actions are triggered.

The POD for the hazard-based trigger system using a predefined threshold was 0.33, while the impact-based trigger system using a varied threshold showed an improved POD of 0.42. Neither system had false alarms. The hazard-based system had eight missed events: one each in 2007, 2008, 2011, 2013, 2014, and 2017, and two during 2010; while the impact-based system had seven missed events: one each during 2008, 2011, 2013, 2014, and 2017, and two during 2010. This shows

TABLE 2. Trigger dates for the hazard-based and impact-based systems.

	Year	Trigger dates
Trigger dates for the hazard-based system, 60%–70% forecast probability, 5 yr RP, and 5-day lead time		
Hazard-based system	2007	4 Jul
	2007	12 Sep
	2012	18 Jul
	2018	20 May
Trigger dates for the impact-based system, 60%–70% forecast probability, varied thresholds, and 5-day lead time		
Impact-based system	2007	4 Jul
	2007	5 Aug
	2007	12 Sep
	2012	18 Jul
	2018	23 May

that the two trigger systems are comparable in detecting flood events and minimizing "actions in vain." Regarding the trigger dates, both systems trigger actions simultaneously for the common triggers (Table 2). However, an additional trigger occurred for the impact-based system on 5 August 2007.

Severe impacts were reported for some of the years when the forecast did not reach the required threshold in both systems (missed events). For example, in 2010, flooding affected more than 7000 people in April across several subcounties in Katakwi. In May and September, waterlogging resulted in crops rotting, with more than 240 gardens destroyed (UNISDR 2018). The highest flow magnitude reported in 2010 at five days LT was in May at 1.5-yr RP. The impacts, therefore, could be because of flash floods and not riverine flooding. Similarly, impacts were reported in 2008, 2011, 2013, 2014, and 2017 across several locations in Katakwi.

Investigating the missed events further shows that, in 2010, the flow magnitude was at 3-yr RP in May at 10 days LT, but it was still below the set threshold; hence, no triggering was required. In September 2011, although the magnitude was at 3-yr RP at five days LT, a magnitude of 10-yr RP was reached at 10 days LT, which could have resulted in the reported impacts (Table 1). In 2013, the magnitude was 3-yr RP in August but resulted in a missed event since the forecast probability was below 60%. In 2014 and 2017, the magnitudes were at 2-yr RP even at longer LT; hence, no actions were triggered.

For the case study in Katakwi, we note slight differences between the hazard-based and the impact-based trigger systems on the thresholds. For example, lowering the trigger threshold during the harvesting period to 3 years only results in one additional trigger. This can be associated with other variables, such as the forecast probability and the action lifetime, which also play a crucial role in trigger variable selection.

d. Does the impact-based trigger system change how anticipatory actions are targeted?

According to the EAP for Uganda, pre-agreed actions would be triggered through the Disaster Relief Emergency Fund (DREF) if high-magnitude flooding (above 5-yr RP) is expected (International Federation of Red Cross and Red Crescent Societies 2020b). Based on these attributes, trigger thresholds would have been reached in 2007, 2012, and 2018 within the hazard-based system and the pre-agreed actions according to the EAP guidelines implemented.

The defined IbFEWtS, which includes the crop cycles from the cropping calendar, shows that actions can be more targeted to correspond to the time of the agricultural season. For example, in 2007, the trigger dates would have occurred during harvesting (July, August) and the start of the second planting season (September), resulting in different actions each time. Actions during the harvesting season could include recommending early harvesting and provision of storage kits, while planting season actions would call for late planting, draining water from farms, and other farm management activities (see Fig. A2 in the appendix). These actions have been derived from farmers' coping practices during the field interviews (Mitheu et al. 2022). The crop cycles, therefore, can be used to tailor interventions with an improved chance of protecting livelihoods at the community level.

4. Discussion

Anticipatory actions are increasingly being taken before an extreme weather event (Wilkinson et al. 2018), with humanitarian organizations using forecasts to inform interventions

Hazard-based model			**Impact-based model**		
	Impacts	No impacts		Impacts	No impacts
Forecast	Hits (4)	False alarm (0)	Forecast	Hits (5)	False alarm (0)
No forecast	Miss (8)	CN(3)	No forecast	Miss (7)	CN(3)
POD (0.33)	hits/(hits+misses)		**POD (0.42)**	hits/(hits+misses)	
FAR (0)	False alarm/(hits+ false alarm)		**FAR (0)**	False alarm/(hits+ false alarm)	

Triggered, with impacts
Triggered, no impacts
Not triggered, with impacts
Not triggered, no impacts

FIG. 5. Contingency tables for the two trigger systems and their computed POD and FAR.

(FAO 2021; World Food Program 2021). Evidence suggests that taking preparedness actions before a hazard can result in significant benefits (Gros et al. 2019). However, hazard-based early-warning systems based on predefined trigger thresholds and pre-agreed actions could result in the exclusion of low-magnitude flood events, which can still result in significant livelihood impacts to the most vulnerable communities at critical times of the agricultural year. The FbA approach focuses on extreme events that are not likely to occur every year (Red Cross Red Crescent Climate Centre 2022), and most humanitarian organizations prefer predefined hazard-based systems for various beneficial reasons, such as avoiding delays associated with real-time decision-making (see Boult et al. 2022). However, decisions on where and when to act and what preparedness actions to take call for local information from at-risk communities (Klassen and Oxley 2021).

Drawing from the Katakwi case study, we discuss the overall benefit of an impact-based trigger system. More specifically, we discuss the value of local information in developing a trigger system and the need for more targeted anticipatory actions. Last, we provide insights into whether the existing hazard-based trigger system should be changed entirely, based on local information, or just the targeting of interventions to protect local at-risk communities.

a. Would integrating local information into a trigger system improve the skill?

A predefined trigger threshold ensures that actions can only be triggered if that threshold is reached. Such a criterion has known benefits (Boult et al. 2022). For example, predefined thresholds reduce subjectivity, which can result from varying the thresholds depending on the situation. However, with the level of impacts changing across specific users or user groups (Stephens et al. 2016), a general predefined trigger based on a danger threshold could result in not enough warnings, leaving out events that could result in significant local impacts (Potter et al. 2021). An alternative is using variable thresholds to define triggers at which actions should be taken, for example, designing flexible thresholds based on real-time expert judgement (Boult et al. 2022) or operationally integrating forecasts with local information to define the trigger thresholds, as applied here.

The choice of the trigger threshold at which actions should be taken can determine the system's skill. While the aim would be to have a trigger system that minimizes false alarms and trigger frequency, decision-makers and humanitarian actors often face the dilemma of when early actions should be triggered, for example, if they should act based on any forecasts to prevent any damages or losses or only based on forecasts that show a high likelihood of event occurrence to minimize expenses. Lopez et al. (2020) provides a detailed explanation of the two decision criteria. The choice of the trigger threshold, therefore, can be subjective and will depend on the sector-specific decisions.

Trigger thresholds can be determined using several methods, as noted in the scholarly literature (Coughlan de Perez et al. 2016; Lopez et al. 2020). This study has shown that these thresholds can be further varied based on context-specific information such as crop calendars and livestock sale schedules to improve the targeting of anticipatory actions, for example, by adjusting the threshold so alerts for low-magnitude floods are triggered only during critical times of the years when low-cost interventions can be initiated through existing disaster management structures (MacLeod et al. 2021).

In the Katakwi District, integrating the crop cycles with flood forecast information allowed us to subjectively vary the trigger threshold across the crop cycles to define an impact-based trigger system. Evaluating the POD using historical flood impacts information showed an improvement in flood detection from the existing hazard-based trigger system (Fig. 5). However, the number of missed events remained high, even for the IbFEWtS, which affects the overall skill. For example, in 2010, though severe impacts were reported in April, May, and September (Table 1), the flow magnitude was at 3-yr RP, even at longer lead times. Therefore, the flood impacts reported could have resulted from flash floods and not necessarily riverine flooding. In contrast, 2011 was reported as a missed event at 5-days LT since the flow magnitude was below 5-yr RP, but the flow magnitude reached a 10-yr RP at 10 days LT. This means that the flood event may have occurred, although not at the date that was forecast, which explains the impacts that were reported during that period (Table 1).

Our findings show that other forecast features, such as the forecast probability and the forecast lead time, also play a crucial role in developing a trigger system. Therefore, forecasts should be monitored beyond the set criteria and actions triggered if necessary. For Katakwi, floods that are likely to reach the 3-yr RP during harvesting and 5-yr RP during the second planting season can be monitored at longer lead times and actions taken if they show a high probability of occurring. For example, in September 2011, high-magnitude floods (10-yr RP) were correctly forecast at 10 days LT, which can be used to trigger early actions.

Overall, local information can be used to adjust trigger thresholds at which different actions should be taken (Stephens et al. 2016; Ciampi et al. 2021). However, the costs and benefits associated with varying the thresholds to trigger anticipatory actions should be investigated (Bischiniotis et al. 2019; Lala et al. 2021). In addition, the quality and quantity of impact information that varies across contexts and locations (Mitheu et al. 2023) and the relevant forecast features (lead time, probability) will determine the overall skill of the resulting triggers. A combination of these variables should be codesigned with the stakeholders to ensure an optimal trigger system is developed.

b. The need for more targeted early actions

The existing hazard-based system triggers pre-agreed actions (Fig. A2 in the appendix) based on the set criteria within the EAP. However, these pre-agreed actions might not fully benefit at-risk communities due to the context-specific nature of their needs and coping practices. For example, interventions such as cash transfers may not be appropriate in all locations if

the market's functionalities (accessibility and availability of a required commodity) are likely to be affected (Bailey and Harvey 2015; Wilkinson et al. 2018). In contrast, targeted anticipatory actions can ensure that communities effectively implement the proper coping practices during a specific time in the agricultural season. Anticipatory actions, therefore, should be designed based on user-specific needs and practices (WMO 2015), which change across users and over time.

In the case of the Katakwi District, most impacts of floods on crops occurred during the harvesting season, based on the calendar that was used (Table 1; Fig. 4). Therefore, information on the crop cycles can be used to design actions to help these communities protect their livelihoods during these critical times. Such local information can also ensure that interventions are better designed. For example, more frequent floods might only require no-regret actions such as raising awareness of the likelihood of impactful flooding. Local farmers can then use such information to inform their coping practices and improve their resilience to floods.

Although we have used a generic crop calendar derived from FEWS NET (2013) (Fig. 3), we note that specific major crops may have overlaps between the harvesting and second planting season where, for most crops, the harvesting season may be extended up to December. For example, a crop like sweet potato grown in Eastern Uganda has a harvesting period starting from July to December, while a crop like groundnut has the harvesting season running from June to August (FAO 2022). The design of targeted actions for specific crops, therefore, should take into consideration such variations in the cropping calendar.

c. *Should the hazard-based trigger system or just the targeting of the interventions be changed?*

The appropriate danger thresholds used in the different EAPs are selected through a consultative process. The process involves disaster managers, alongside forecasters, to 1) select the hazard threshold that could lead to significant losses and 2) decide on the acceptable number of times that they may be willing to take actions "in vain," that is, actions that are not followed by an extreme event. For example, in Uganda, the threshold was set at 5-yr RP with an acceptable probability to act in vain of 50%. In the FbA approach, this would mean targeting events that are unlikely (a 20% chance) to happen each year and leaving out low-magnitude events, which might result in high impacts at specific times of the year, for example, the crop-fruiting phase.

Given this and based on the LIMB framework (Ciampi et al. 2021), the crop cycle information has been integrated with forecast information to develop a trigger system that allows variable triggers and different interventions for communities at risk from flooding. The context-specific information incorporated within the impact-based system will vary according to the hazard and the location of interest. Therefore, deciding whether to change the entire system or just a single component (e.g., the selected actions or the thresholds) is not straightforward. Here we highlight two possible recommendations:

1) The existing hazard-based trigger system (Fig. 4a) can be enhanced by integrating livelihood-based information, such as the crop cycles, to help better target the preagreed actions. For Katakwi, this would mean having four triggers [2007 (2), 2012, and 2018] with different interventions based on the crop cycles (Fig. A2 in the appendix). Crop calendars will vary across countries and districts and should be developed in consultation with the local communities. For example, Uganda has more than 11 crop calendars across different climate zones (FAO 2022). Codesigning pre-agreed actions with local stakeholders is crucial to properly reflect households' various coping strategies at different times of the year. To avoid replication, the codesign of targeted actions should also consider the current practices reflected in the disaster management plans (Stephens et al. 2016). For example, in Katakwi, some priority coping practices within the agricultural livelihood sector include postharvest handling and seed distribution (Katakwi District Local Government 2017).
2) An impact-based trigger system (Fig. 4b) could be developed based on variable triggers and crop cycles. The choice of the trigger thresholds across the crop cycles must be codesigned with stakeholders based on the decision-making context (e.g., livelihood coping strategies). Historical impact information can then be used to evaluate the trigger system in comparison with the existing system to assess if it is necessary to develop a new trigger system. The evaluation using historical impact information, however, can result in uncertainty. Notably, the quality and quantity of the impact information available for each location can vary greatly (Mitheu et al. 2023). In such circumstances, historical impact data should be used alongside other available and relevant data based on the location to evaluate the trigger system, for example, including rainfall for cases of flash floods (Yang et al. 2015). The available impact data should also be used with caution, and local knowledge from the communities should be used to enhance them. In addition, the impact data can be disaggregated to the various subcategories and the relevant information used (Kruczkiewicz et al. 2021). For example, impacts because of flash floods may not be useful in evaluating riverine flood forecasts. However, such information can ensure the design of appropriate interventions for each flood type (Paprotny et al. 2021).

For the Katakwi case study, an improved POD and reduced number of missed events are seen between the existing hazard and the defined impact-based trigger system. However, the false alarms, and the trigger dates are similar in the two systems. This could have resulted due to the length of the data records (12 years) used in the analysis and might be different if more flood events are considered. Based on these findings, the existing hazard-based trigger system could remain the same in a humanitarian context, but early actions could be further enhanced using crop cycles. The impact-based trigger system can then be further examined in a different context (e.g., for livelihood protection) to assess the value of this contextual information. Although a slight difference is noted

between the two systems, the impact-based system is still relevant to show the use of local information to adapt global forecasting systems to local contexts and how anticipatory actions could be better targeted.

Overall, we have provided recommendations on how local information can contextualize and enhance hazard-based trigger systems and ensure variable trigger thresholds and more locally targeted actions. We also acknowledge that a decision on whether to change a trigger system would require clarity in understanding the benefits and consequences of implementing the new method, which will vary across communities and locations. In addition, the decision to implement might not be straightforward and will depend on background issues shaping the implementing agencies' political and institutional environment. Our findings should, however, open avenues for further dialogue on what the impact-based trigger system could mean within the broader FbA landscape toward building the resilience of at-risk communities.

d. *Future work*

The shift from hazard-based to impact-based forecasting would ensure that users and communities have access to the forecasts and advisories on the likely impacts of any extreme threatening event. Therefore, to implement effective preparedness measures at the community level, locally customized EWI will be required due to the context-specific needs and priorities among communities (Bailey et al. 2019). Therefore, local contextual information plays a crucial role in improving the trigger models by ensuring that household-level anticipatory actions are designed.

In this study, data on crops and how they are affected by floods were used to redefine the trigger model. We note that local information will be context-specific and additional data collected from the communities can be used to provide the required personalization of the impact-based trigger model. Future work, therefore, can look at the collection of additional information such as personal trigger preferences, anticipatory actions preferred by communities, flood impact perception, and location specific impacts on other amenities such as roads and markets. Such data can then be used to develop impact-based trigger systems that are sector relevant.

5. Conclusions

The study findings show that contextualized livelihood information can enhance the development of variable trigger thresholds and more targeted anticipatory actions. Hazard-based systems, therefore, can be adapted to the local context to ensure that even at-risk communities are protected. However, developing an impact-based trigger system requires sustained engagement with local communities to ensure their inputs are included in the design and to facilitate the collection of HEA information to understand the livelihoods systems of the local communities and the differential coping strategies. Furthermore, to broaden the usefulness of the defined trigger system, in-depth consultations with the relevant stakeholders in different sectors can be undertaken to develop the criteria required to tailor the impact-based trigger system to sector-specific decisions.

Integrating the local contextual information with forecast information has shown that even data-scarce regions can benefit from impact-oriented approaches based on qualitative criteria. The approach can be tailored to ensure improved preparedness for flood risks at the community level. An impact-based system can also be very useful in supporting the existing hazard-based systems to build more confidence in their use in informing anticipatory actions.

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Data availability statement. The field data collected and analyzed during the study are included in this article in the form of tables and figures. The GloFAS v3.1 reforecasts are available from Copernicus Climate Change Service Climate Data Store (https://cds.climate.copernicus.eu/). Impacts reports from DesInventar and EM-DAT are freely available from their respective web pages (https://www.desinventar.net/ and https://www.emdat.be/database).

APPENDIX

Additional Figures

Figure A1 lists positive impacts of floods on fruit trees in Katakwi District, and Fig. A2 describes the pre-agreed early actions, along with the targeted early actions that were derived from farmer interviews.

Time of Year	December	January	February	March	April	May	June	July	August	September	October	November
Rainfall Season												
Fruit_trees/calendar	H	LAND PREP		PLANTING & WEEDING			HARVESTING [H]			PLANTING		H
Lemon												
Oranges												
Mango												
Papaya												
Jack fruit												

FIG. A1. Positive impacts of floods on fruit trees in the three villages in Katakwi District.

Pre-agreed Early actions drawn for EAP for Uganda									
Community awareness on anticipated risks and selected early actions									
Distribution of water purification chemicals, water storage vessels and soap									
Distribution of cash and voucher assistance to facilitate evacuation and meet other basic needs									
Distribution of customised shelter kits									
Cleaning water sources/ desilting drainage channels/ dredging in urban and rural areas									
Community mapping- (map out designated centres, evacuation routes and holding stores)									
Early actions based on the crop calendar (derived from interviews with farmers.)									
Months	March	April	May	June	July	August	September	October	November
Contextualized Early actions	Late planting of early maturing crops Draining water from farms to protect crops. Farm management practices to improve soil drainage.			Early harvesting of major crops such as cassava, sweet potatoes etc. Provide kits to ensure storage of harvests in a dry place.			Late planting of early maturing crops Draining water from farms to protect crops		
							Legend Planting period Harvesting period		

FIG. A2. Pre-agreed early actions (from the Uganda EAP) and the targeted early actions derived from farmers' interviews.

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