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SPECIAL ISSUE

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Advancing operational flood forecasting, early warning and risk management with new emerging science: Gaps, opportunities and barriers in Kenya

Augustine Kiptum[1,2] | **Emmah Mwangi**[1] | **George Otieno**[3,4] | **Andrew Njogu**[2] | **Mary Kilavi**[2] | **Zacharia Mwai**[2] | **Dave MacLeod**[4] | **Jeff Neal**[4] | **Laurence Hawker**[4] | **Tom O'Shea**[4] | **Halima Saado**[5] | **Emma Visman**[6,7] | **Bernard Majani**[6] | **Martin C. Todd**[1]

[1]Department of Geography, University of Sussex, Sussex, UK
[2]Kenya Meteorological Department, Nairobi, Kenya
[3]Water Resources Authority, Nairobi, Kenya
[4]University of Bristol, Bristol, UK
[5]Kenya Red Cross Society, Nairobi, Kenya
[6]King's College London, London, UK
[7]UK Centre for Ecology and Hydrology, Bailrigg, UK

Correspondence
Augustine Kiptum, Department of Geography, University of Sussex, Sussex, UK.
Email: ak720@sussex.ac.uk

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Abstract
Kenya and the wider East African region suffer from significant flood risk, as illustrated by major losses of lives, livelihoods and assets in the most recent years. This is likely to increase in future as exposure rises and rainfall intensifies under climate change. Accordingly, flood risk management is a priority action area in Kenya's national climate change adaptation planning. Here, we outline the opportunities and challenges to improve end-to-end flood early warning systems, considering the scientific, technical and institutional/governance dimensions. We demonstrate improvements in rainfall forecasts, river flow, inundation and baseline flood risk information. Notably, East Africa is a 'sweetspot' for rainfall predictability at sub-seasonal to seasonal timescales for extending forecast lead times beyond a few days and for ensemble flood forecasting. Further, we demonstrate coupled ensemble flow forecasting, new flood inundation simulation, vulnerability and exposure data to support Impact based Forecasting (IbF). We illustrate these advances in the case of fluvial and urban flooding and reflect on the potential for improved flood preparedness action. However, we note that, unlike for drought, there remains no national flood risk management framework in Kenya and there is need to enhance institutional capacities and arrangements to take full advantage of these scientific advances.

KEYWORDS
early warning, flood, forecast-based action, forecasting, impact based forecasting, inundation, Kenya

1 | INTRODUCTION

Globally, there are rising concerns about the frequency, magnitude and severity of disasters resulting from extreme weather/climates with flood events becoming the dominant disasters in the recent past (CRED, 2022). Floods affect more people than any other geophysical hazard and account for 31% of global economic losses caused by all natural hazards (UNISDR, 2015a, 2015b). African populations are particularly exposed to climate-related risks due to the continent's high levels of poverty, vulnerability, and very ineffective risk management systems (Abdrabo et al., 2014). In terms of the number of people affected, flood risks in Africa, and East Africa in particular, are on a rising trend overtaking drought in terms of number of people affected (Di Baldassarre et al., 2020; Haile et al., 2020; Lumbroso, 2020).

The economic costs of flooding in Kenya specifically are estimated to average 0.8% of annual national Gross Domestic Product (GDP), and in extreme flooded years (e.g., the 1997–1998 Indian Ocean Dipole/El Niño event) losses can be much higher (11% of GDP), arising primarily from loss of lives, infrastructural damage, agricultural losses from crops and livestock, disruptions and incidences of waterborne/sanitation diseases (GoK, 2018). Further, floods cause most disaster-related fatalities and result in extensive displacement of people. The floods in Kenya by end of May 2020 claimed up to 230 lives, displaced close to 350,000 people, affected approximately 800,000 according to United Nations Children Emergency Fund and led to active cholera outbreaks in five Kenyan counties (UNICEF, 2018). The response cost then to the Kenyan government was estimated at US $1 billion (GoK, 2019). There is also reported to be a clear increase in the frequency and intensity of reported climate-related impacts in recent years with some case studies projecting a likely increase in flooding due to extreme rainfall events (Fourth, 2011; World Bank, 2021).

Future flood risk in Kenya is likely to increase due in large part to increasing populations living in flood-prone areas (Abdrabo et al., 2014). Future changes in flood hazard themselves are an outcome of complex interaction of changing rainfall characteristics, the nature of the land surface and river regulation, the impact of which is space/time dependent. The fluvial flood hazard is projected to increase over Kenya (Hirabayashi et al., 2013), due in part to projections of an increase in rainfall especially during the short rains season (Rowell et al., 2015), although uncertainty still remains (Dankers et al., 2014; Döll et al., 2018). Latest projections continue to suggest future increases in mean annual rainfall over East Africa, although the ‘paradox’ between recent and future trends remains to be fully resolved (Rowell et al., 2015).

Both fluvial and pluvial flooding is expected to increase vulnerability to inhabitants in both riparian and informal settlements due to projected increases in rainfall intensity from climatic changes (Masson-Delmotte & Zhai, 2021). A Flood Early Warning System (FldEWS, Figure 1) provides a set of capacities needed to generate and disseminate timely and meaningful warning information that enables at-risk individuals, communities and organisations to prepare and act appropriately and in sufficient time to reduce the harm or loss caused by floods. FldEWSs are a common intersection of various agendas towards disaster risk reduction, effective humanitarian intervention and climate resilient and sustainable development, and addresses current, emerging and future flood-related risks. However, there remains a clear deficit in FldEWS in Africa relative to other parts of the world (Lumbroso et al., 2016; WMO, 2020). Within Kenya specifically, Disaster Risk Management is the first strategic action area of the Adaptation Technical Analysis Report (GoK, 2018), which supports the National Adaptation Plan (GoK, 2016). Improving early warning is earmarked as a clear priority, with a target to extend FldEWS coverage in flood-prone areas in at least half of the flood-prone counties. At the same time efforts to climate-proof infrastructure and other flood protection measures are prioritised.

In this paper, we present the results of a research which aims to inform and guide efforts towards improving FldEWS in Kenya by:

i. Analysing the status of FldEWS and governance in Kenya to identify key priority gaps and limitations (Section 2).
ii. Presenting new risk analysis and forecasting research to address the gaps identified (Section 3).
iii. Specifying priority recommendations to take advantage of the opportunities presented in (ii) (Section 4).

In doing so, the paper considers the five components of WMO Multi-Hazard EWS ‘value chain’(WMO, 2020), which conceptually represents an ‘end-to-end’ EWS (Figure 1) and can be extended to Impact based Forecasting (IbF) which is a forecasting ‘paradigm shift’ from ‘what the weather will be’ to ‘what the weather will do’ (Met Office, 2022; WMO, 2015).

2 | ANALYSING THE STATUS OF FLOOD RISK MANAGEMENT IN KENYA CRITICAL GAPS AND LIMITATIONS

To identify the critical gaps and limitations in FldEWS in Kenya, we undertake a comprehensive assessment and

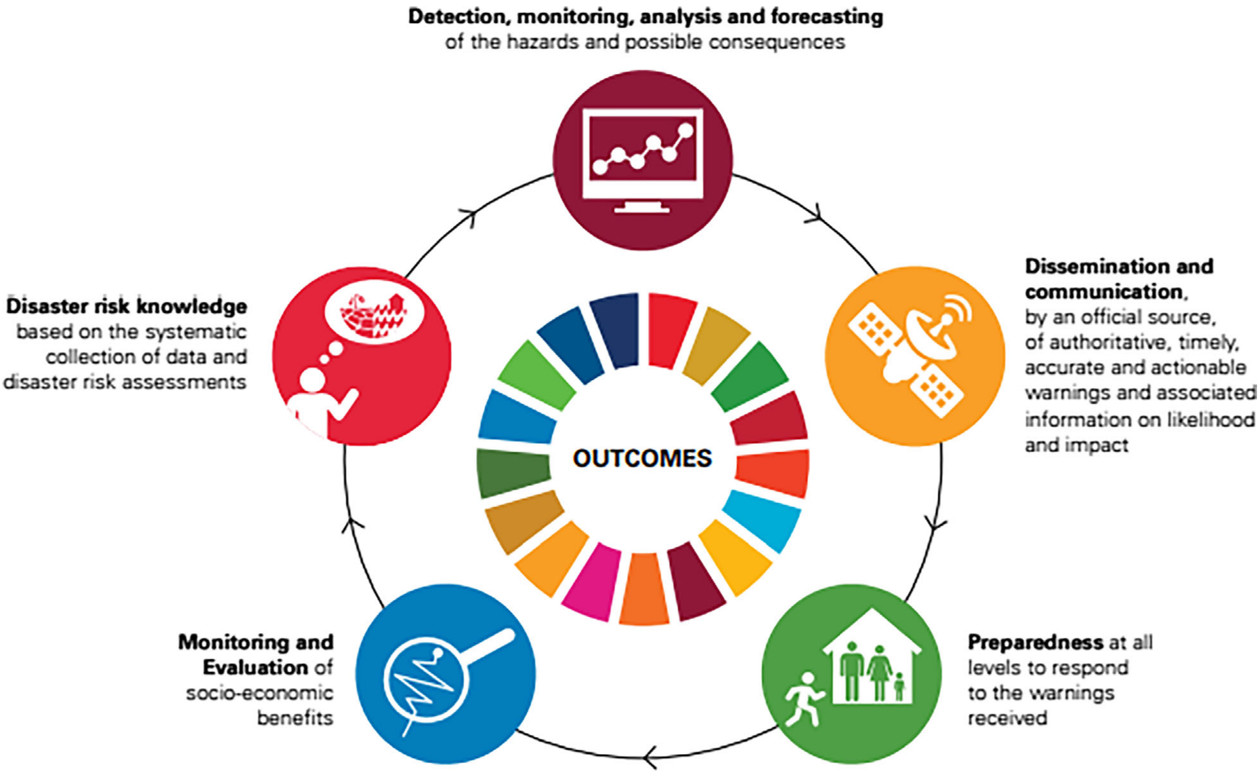

FIGURE 1 The five main end-to-end components of WMO Multi-Hazard Early Warning System (MHEWS). Disaster risk knowledge (Component 1—exposure and vulnerability), detection, monitoring analysis and forecasting (Component 2), Dissemination and communication (Component 3), preparedness (Component 4) and Monitoring and evaluation (Component 5; WMO, 2020)

analysis of the current status, considering first flood risk governance structures (Section 2.1) and then the various components of FldEWS as presented in Figure 1 (Sections 2.2–2.4). We draw on a systematic analysis of relevant policy documents and operational systems. On this basis, we identify critical gaps and limitations (see Section 2.5) which we then address in Section 3.

2.1 | Governance and institutions for flood risk management

Responsibilities for flood risk management, including operational FldEWS, are complex and shared across multiple agencies and indeed administrative levels, as Kenya has a decentralised system of governance. Relevant mandates emerge from a comprehensive set of national policies and acts covering both disaster and water resources management. A comprehensive summary is provided by (Weingärtner et al., 2019)—see their Annex 8. The World Bank funded Kenya Water Security and Climate Resilience Program (KWSCRP, 2013–2022, https://kwscrp.org/) has made, and continues to make, a critical contribution to governance and institutional capacities, notably by facilitating and supporting the legal framework set out by the Water Act of 2016. Institutional mandates, and therefore responsibilities for various components of EWS (Figure 1), have been recently clarified as follows:

- The Water Resources Authority (WRA) has the responsibilities for water resource management as well as flood mitigation, including monitoring and observation of surface water (e.g., river flows) and flood hazard events, and mapping flood risk (contributing to Components 1 and 2 in Figure 1 see Section 2.2.1). To that end, the WRA has established the National and Regional Flood Mapping and Impact Assessment Centres (FMIAC).
- Kenya Meteorological Department (KMD) has the responsibility for flood forecasting, including issuance of extreme event warnings (Figure 1, Components 2 and 3) conducted by the newly established National Flood Forecasting and Early Warning Centre (NFFEWC). Flood advisories and alerts are disseminated to disaster risk agencies, including national and county governments and humanitarian organisations. WRA and KMD recently signed a 5-year Memorandum of Understanding (MoU) to ensure effective integration of these related activities.

- Flood (and other disasters) preparedness, response and monitoring (Components 4 and 5 of Figure 1) are responsibilities at the national level and lie with: The National Disaster Operation Centre (NDOC) which is an inter-agency institution that monitors, coordinates and mobilises resources for disaster preparedness and response; and the National Disaster Management Unit (NDMU), which is part of the Kenya Police Service (KPS) and coordinates disaster management with other institutions and ministries. The government also works with humanitarian and development agencies which are coordinated under Kenya Humanitarian Partnership Team (KHPT). As an auxiliary to the government, the Kenya Red Cross Society (KRCS) works closely with national and county governments in flood risk response and is active in enhancing FldEWS see (see Sections 2.4.2 and 2.4.3).

Reflecting on these structures, there has been some indication of limited coordination and overlapping of roles and responsibilities amongst institutions, which can weaken flood response and preparedness (Weingärtner et al., 2019). Moreover, at the time of writing, there is no single coordinating body for flood risk management in Kenya (unlike for drought), nor a single operational national risk management authority and national Disaster Risk Management (DRM) law, meaning that flood risk management in Kenya is rather fragmented (Development Initiatives, 2017).

2.2 | Existing flood risk assessment and operational FldEWS in Kenya

2.2.1 | National flood risk assessment and monitoring

For water resources regulation by the WRA, Kenya has administratively been divided into 6 river basins (Figure 2). For flood risk management, The Kenya Water Master Plan, 2010 has identified 21 flood-prone areas at river basin and urban scales. Essential historical flood risk information (Component 1, Figure 1) should cover Flood hazard from hydro-meteorological observations and mapping of inundation extents; Information on societal vulnerability and exposure to flooding as well as the actual observed impacts, in terms of losses and damages. Together, these data form the basis of flood risk mapping (vital also for climate change risk assessment), calibration and validation of hydrological models for flood forecasting and derivation of flood impact functions to support IbF.

WRA operates a network of 279 surface water monitoring river gauges (with 39 telemetric, 95 automatic and 152 manual stations location map shown in S1; GoK, 2019). The WRA FMIAC, operating at both national and regional (basin) levels is responsible for mapping historical flood risk and monitoring flood inundation and collating vulnerability data, and supporting formulation of flood contingency plans. The capacity of the FMIAC is currently being enhanced through the KWSCRP. For example, WRA undertook a detailed flood risk mapping for priority areas in the Lake Victoria basins in southwest Kenya (Figure 2 areas 1–5). Activities included near real-time flood assessment using available remote sensing data (see example image in Figure 3). During this flood risk assessment exercise by WRA and other stakeholders responsible for flood risk within the Nzoia basin, Sentinel-2 optical image available from the European Space Agency (ESA) together with a high-resolution flood inundation modelling using the HEC-RAS model tool were combined with a surface digital elevation data at a high resolution of 2 m from airborne lidar (not shown) were used to assess flood economic impacts through overlaying of socio-economic and demographic information from census data. We show an analysis of a flood extent map from sentinel 2 optical image acquired on 20th May 2020 and available for the Nzoia river basin in Figure 3. Using a commonly available spectral water index known as Modified Normalised Difference Water Index (MNDWI) flood extent and inundated areas were estimated by a ratio combination of Short Wave Infrared (SWIR)-Band 11 and green band 3 of the Sentinel 2 image acquired closer to the flood event using Equation 1 below:

$$MNDWI = (\text{Green} - SWIR)/(\text{Green} + SWIR) \qquad (1)$$

2.2.2 | The Nzoia basin FldEWS

At the present, Kenya does not have a FldEWS operational at the national scale (Weingärtner et al., 2019). Figure 4 shows the KMD's NFFEWC that is operational only for the Nzoia River in Western Kenya. However, efforts to expand to other flood-prone basins are currently ongoing which we discuss in detail in the next subsections of this article (see Sections 2.4.1 and 2.4.2). The Nzoia River FldEWS was established in 2008 through World Bank support to the Kenyan government and was aimed at enhancing the flood early warning systems within the basin amongst other project components. This has recently been upgraded under an addendum to KWSCRP (funded by the Korean government) by installing additional monitoring stations and enhancing capacity for flood forecasting at KMD. The current operational FldEWS (Figure 4) is automated using the Water

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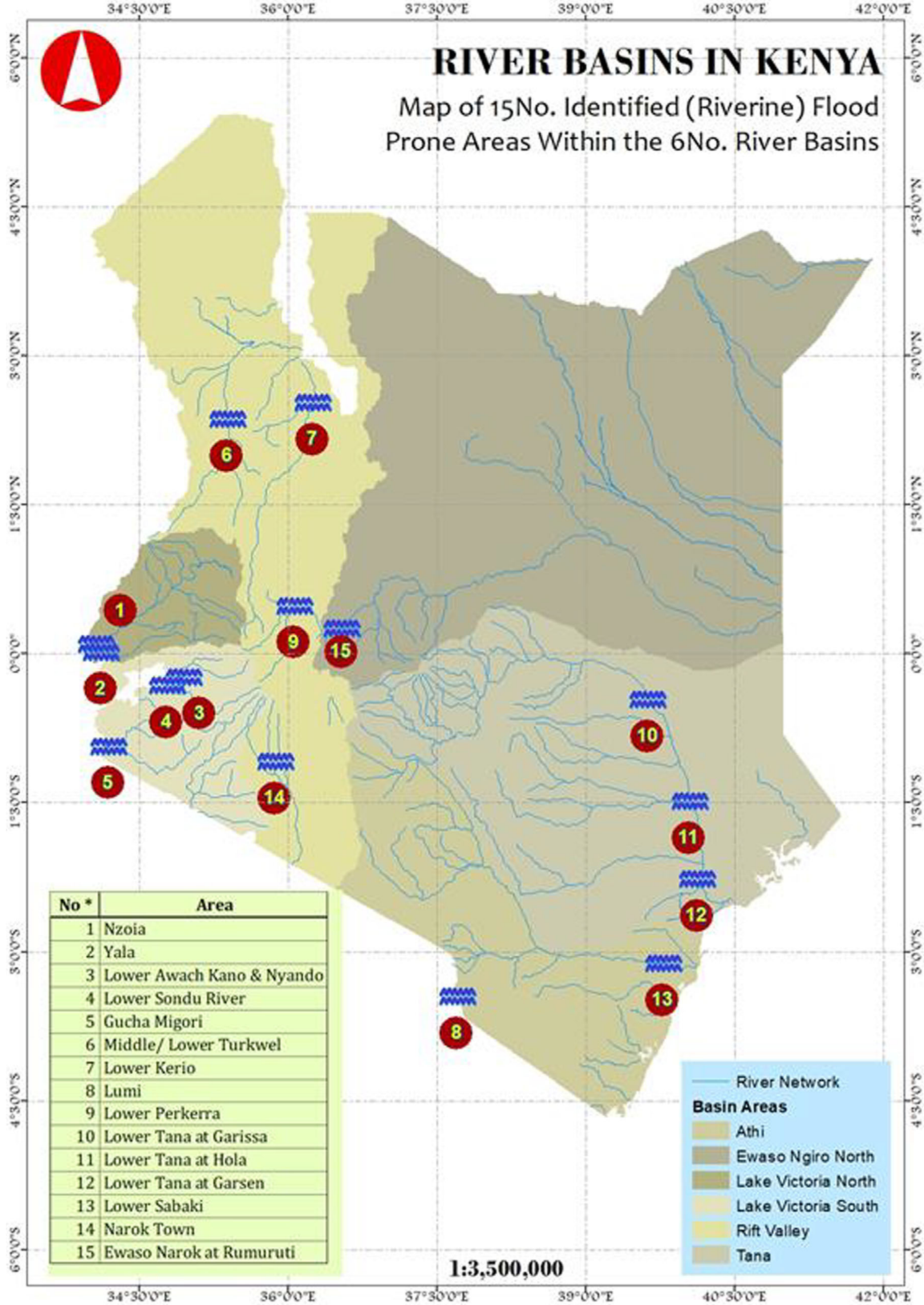

FIGURE 2 Prioritised flood-prone areas within the six river basins in Kenya (*Source*: Kenya Water Master Plan 2010)

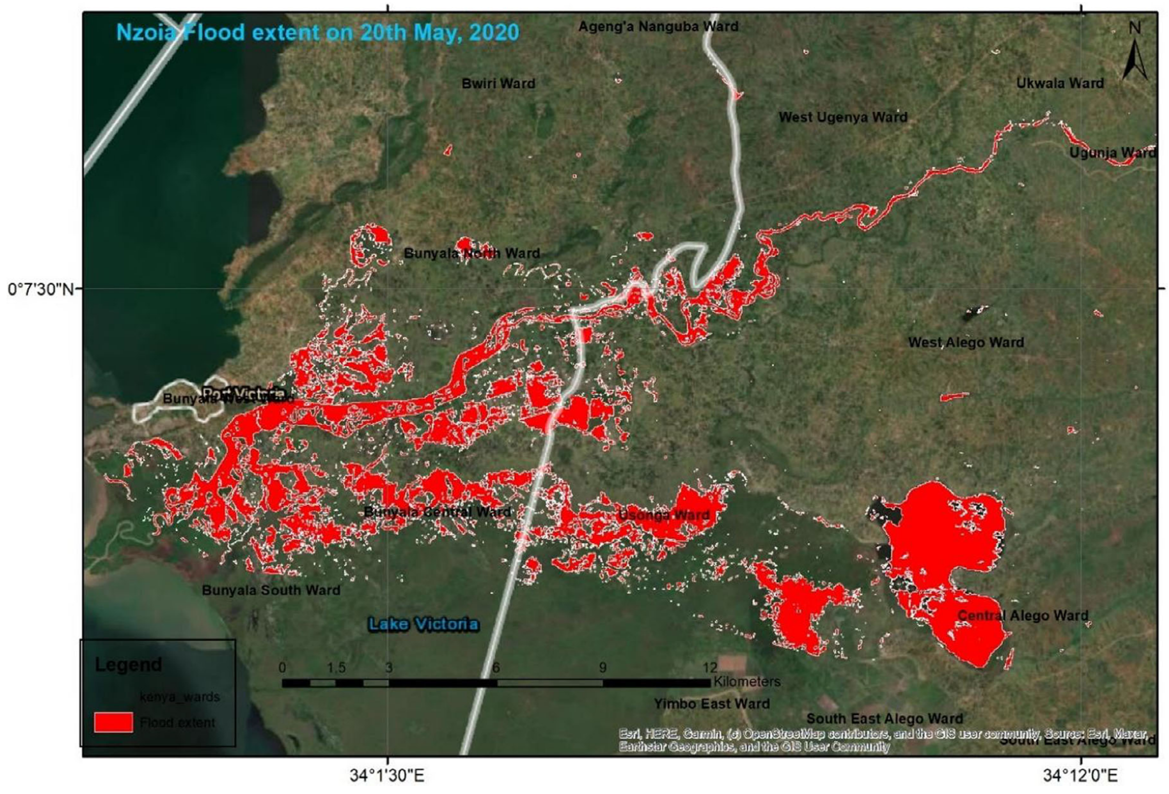

FIGURE 3 Example of a near real-time flood inundation and extent. Flood inundation map for Lower Nzoia River Basin in May 2020 obtained from Sentinel 2 optical image from European Space Agency on 20th May 2020 (ESA, 2022) and is overlaid with affected administrative ward units. Flooded areas are signified by the red colour. See Figure 2 for the location of the Nzoia basin within Kenya

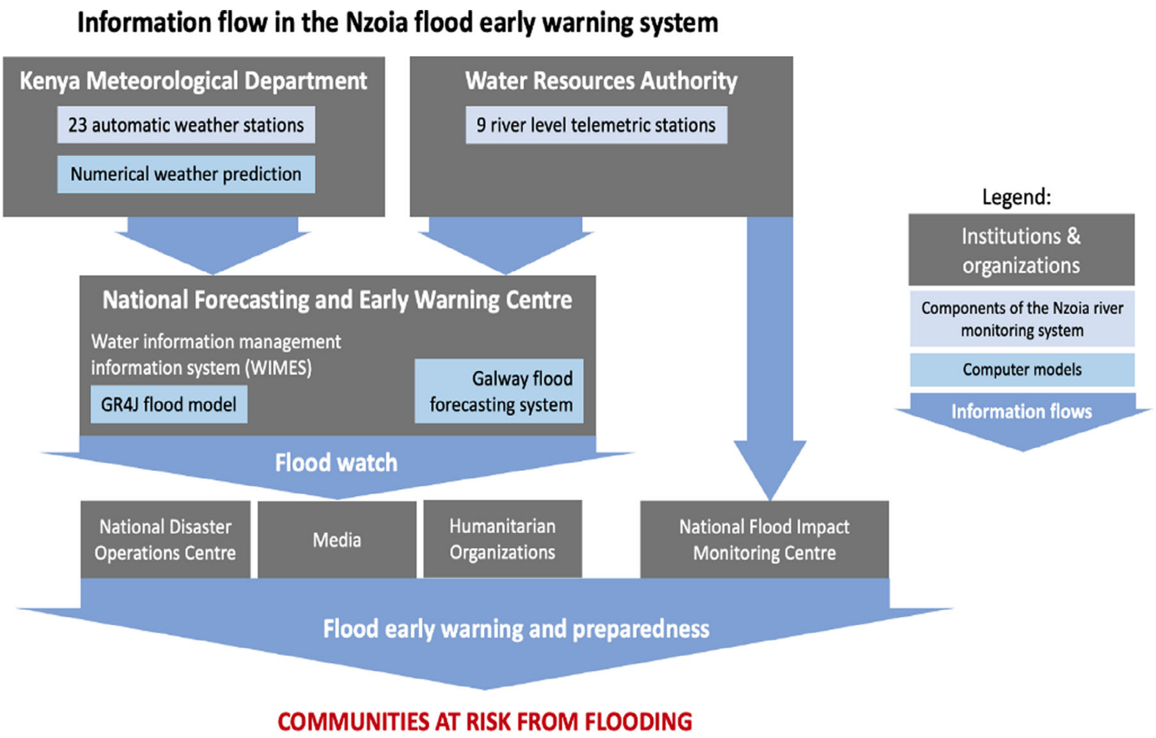

FIGURE 4 Schematic representation of the existing Flood Early Warning System over Nzoia River Basin (See Figure 2 for location of Nzoia river and Figure 5 for location of hydrometeorological stations in the basin)

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Information Management and Ecosystem and Services (WIMES) interface. WIMES ingests hydrometeorological data from 23 telemetric Automatic Weather Stations (AWSs; transmitting data in real-time to the NFFEWC servers), and nine telemetric river gauging stations along the river (transmitting to WRA observation database servers). See Figure 5 for the hydrometeorological network of the Nzoia FldEWS. WIMES uses 3-day lead time rainfall forecasts from the KMD Weather Research and Forecasting (WRF) regional model.

Deterministic river flow forecasts out to 3 days lead time are then generated using the lumped GR4J model (Modèle du Génie Rural à 4 paramètres Journalier) for the nine gauging station locations. Currently, NFFEWC operates the new WIMES in parallel with the previous system based on the Galway Flood Forecasting System (GFFS) model. We present in Figure 4 the operational framework for the NFFEWS for the Nzoia River basin. Flood watch/warning bulletins are then generated automatically based on a pre-agreed template including river level forecasts in relation to flood-related thresholds and expected flood risk for the flood-prone communities, with a 3-day lead time. These are disseminated every day by email from the WIMES interface to basin flood risk stakeholders, including national and specific county's government agencies (i.e., Busia, Siaya and Kakamega), the NDOC, humanitarian organisations and at-risk communities in the basin.

2.3 | Other operational flood-related warnings

2.3.1 | Monitoring-based Tana River basin FldEWS

In the absence of an official operational FldEWS in the Tana River basin (currently under development, see

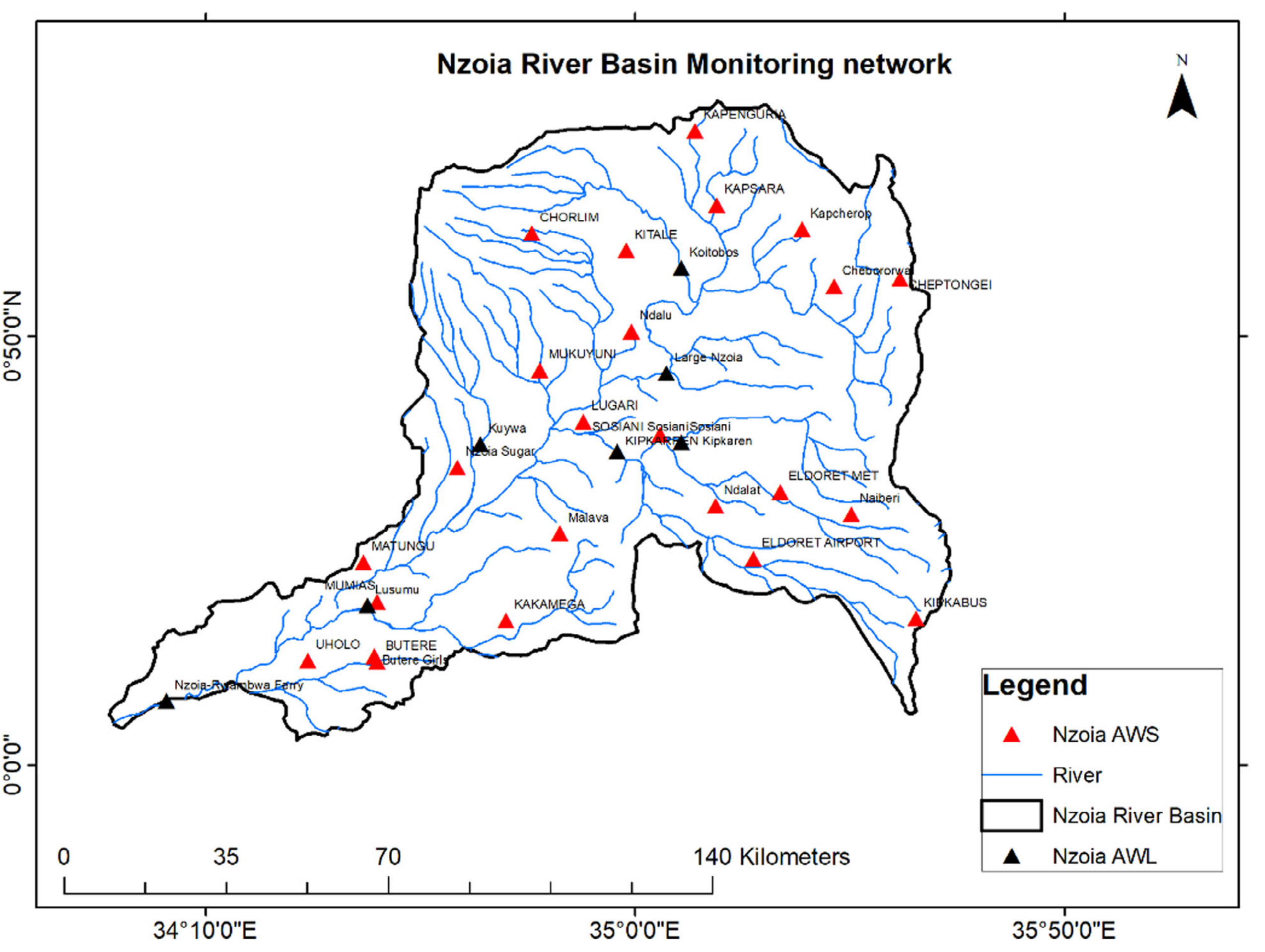

FIGURE 5 Upgraded Nzoia River Basin Automatic Weather Stations (AWS) and Automatic Water Level (AWL) hydrometeorological monitoring network. The AWL gauging station at Rwambwa bridge, used as the target in the Nzoia FldEWS and for verification of the Global Flood Awareness System (GLOFAS; Section 3.2.2), is the downstream most AWL shown here

TABLE 1 River level flood monitoring colour coding system used in Tana River Basin at Garissa station (4G01)

River level and by colour code	Actions
<3.0 m	Normal conditions
3.0–3.5 m	Alert conditions
3.5–4.0 m	Alarm
>4.0 m	Emergency

Section 2.4.1), the WRA regional offices in the counties of Garissa, Tana River and Kilifi together with other flood risk management stakeholders have developed a simple monitoring based FldEWS. Flood warnings for the downstream floodplain areas are triggered through monitoring of river level at the Garissa (4G01), Holla (4G04) and Garsen (4G02) gauging stations when it exceeds some pre-defined thresholds (see location 10 in Figure 2). Table 1 shows the various colour codes used for flood alerts at Garissa station (4G01) as an illustration, where green colour coding indicates that the river is at normal flow conditions when the river level is less than 3 m. A yellow colour code indicates an alert state, which is reached when the river level is between 3.0 and 3.5 m, while an alarm condition is indicated when the river level is between 3.5 and 4.0 m. Whenever the river level exceeds 4.0 m, extreme flood and emergency actions are triggered which in this case is denoted by a red colour code (see Section 2.4.2 on actions to be triggered based on county flood EAPs). The same colour coding system is applied in the other two river monitoring sites of Garsen and Holla but using different river levels (see S1 for the river level monitoring systems for these sites).

The flood warnings are then disseminated to flood risk management stakeholders through a basin-wide WhatsApp group whose membership is drawn from county government departments in the affected counties, KRCS officials, community leaders and so forth. The stakeholders then share this information on other county-based social media platforms. Public communication channels are diverse including social media and word of mouth. Based on these warnings, government and humanitarian agencies as well as the public undertake preparedness actions including evacuation from low-lying areas. Currently, the system operates in an ad hoc manner which implies that the system is operational whenever there is a sudden continued rise in river level at Garissa River monitoring station (RGS 4G01) and the other two sites and mostly during the two main rainy seasons of March–May (long rains) and October–December (short rains).

2.3.2 | Heavy rainfall advisories

KMD issues Heavy Rainfall Advisories (HRA) at the national level as a proxy for possible flood warnings. The HRA are text-based bulletins (see example Figure 6) issued whenever rainfall forecasts are expected to exceed at least 30 mm total rainfall in a period of 24 h with a probability of 33% chance of occurrence in a specific region in the country. These HRA are informed by the output of dynamical atmospheric models from WMO Global Producing Centres (GPCs) as well output from WRF model run at KMD's having a 72-h lead time (3-day) at National Forecasting Centre (NMC). HRAs are only issued with a lead time of up to a few days, with only coarse spatial detail (indicating the potentially affected counties), along with general instructions for flood preparedness (Figure 6). The HRA bulletins are then disseminated to the public and main actors in disaster management including the Ministry of Interior and Coordination of National Government, affected county meteorological offices and KRCS amongst others. KRCS then broadcasts mass mobile phone SMS messages to the populations/communities at risk. While a comprehensive assessment of all archived HRAs suggests the forecast skill has improved in recent years (e.g., Macleod, Kilavi, et al., 2021), there remains a need therefore to verify the HRAs against actual flood data for effective use in taking an early flood preparedness actions.

2.4 | Ongoing initiatives developing FldEWS capabilities in Kenya

Paramount amongst some of the projects in enhancing flood early warning in Kenya is the KWSCRP (Section 2.4.1). In addition, we also summarise other relevant initiatives that have the potential to align with the activities of the mandated agencies WRA and KMD. In Section 3, we identify some of the key advances emerging from these initiatives that could support the operational FldEWS and draw recommendations in Section 4.

2.4.1 | Kenya Water Security and Climate Resilience Projects

Within the broader water resource management objectives of the KWSCRP (Section 2.1 and kwscrp.org) significant investment has been made to enhance FldEWS in Kenya. These, includes focusing on the existing Nzoia River FldEWS (Section 2.2.2) and initiating new FldEWS in other basins to cover the Athi and Tana River basins (Figure 2). This has involved (i) increasing and rehabilitating the

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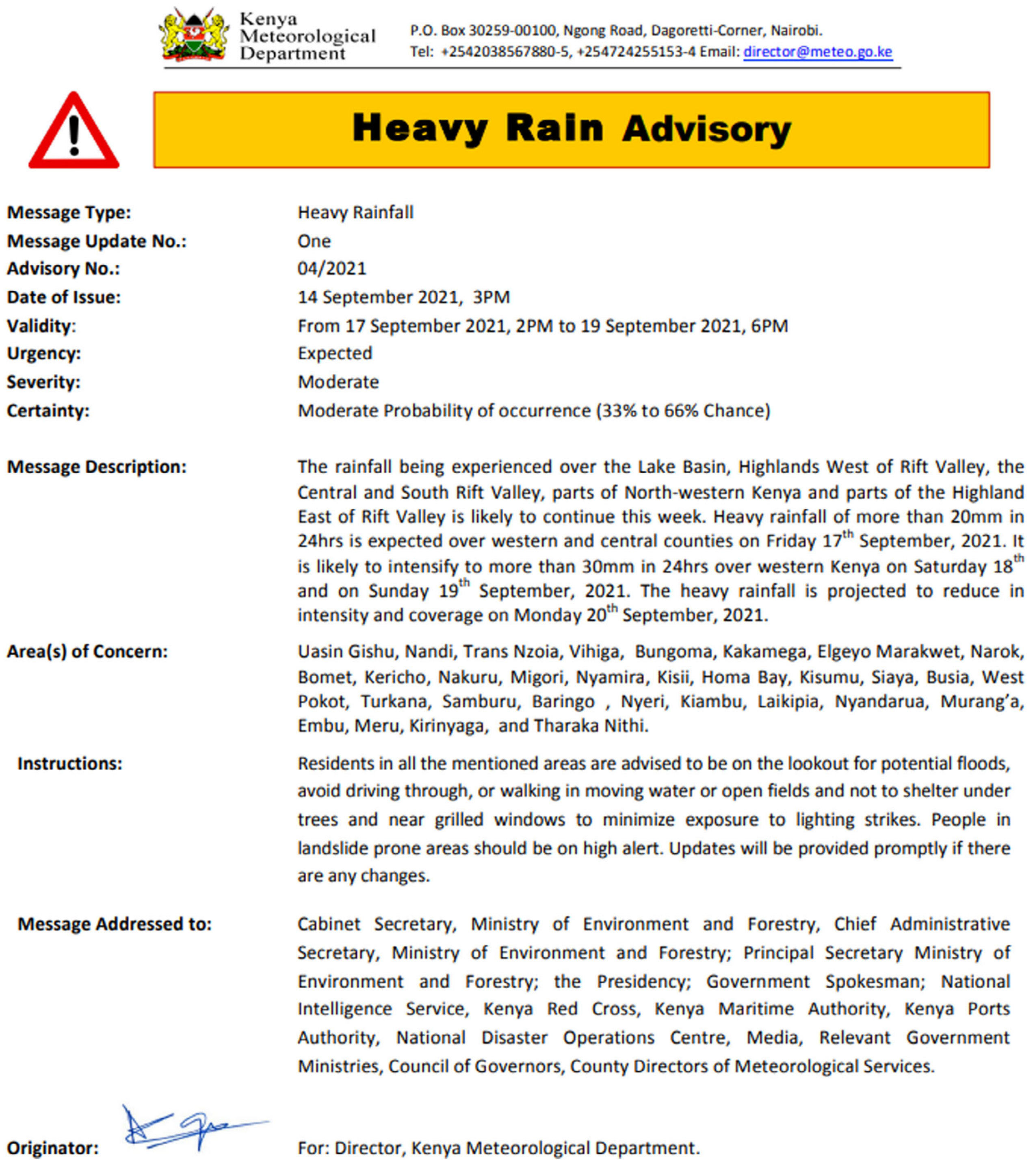

Kenya Meteorological Department

P.O. Box 30259-00100, Ngong Road, Dagoretti-Corner, Nairobi.
Tel: +2542038567880-5, +254724255153-4 Email: director@meteo.go.ke

Heavy Rain Advisory

Message Type:	Heavy Rainfall
Message Update No.:	One
Advisory No.:	04/2021
Date of Issue:	14 September 2021, 3PM
Validity:	From 17 September 2021, 2PM to 19 September 2021, 6PM
Urgency:	Expected
Severity:	Moderate
Certainty:	Moderate Probability of occurrence (33% to 66% Chance)
Message Description:	The rainfall being experienced over the Lake Basin, Highlands West of Rift Valley, the Central and South Rift Valley, parts of North-western Kenya and parts of the Highland East of Rift Valley is likely to continue this week. Heavy rainfall of more than 20mm in 24hrs is expected over western and central counties on Friday 17th September, 2021. It is likely to intensify to more than 30mm in 24hrs over western Kenya on Saturday 18th and on Sunday 19th September, 2021. The heavy rainfall is projected to reduce in intensity and coverage on Monday 20th September, 2021.
Area(s) of Concern:	Uasin Gishu, Nandi, Trans Nzoia, Vihiga, Bungoma, Kakamega, Elgeyo Marakwet, Narok, Bomet, Kericho, Nakuru, Migori, Nyamira, Kisii, Homa Bay, Kisumu, Siaya, Busia, West Pokot, Turkana, Samburu, Baringo , Nyeri, Kiambu, Laikipia, Nyandarua, Murang'a, Embu, Meru, Kirinyaga, and Tharaka Nithi.
Instructions:	Residents in all the mentioned areas are advised to be on the lookout for potential floods, avoid driving through, or walking in moving water or open fields and not to shelter under trees and near grilled windows to minimize exposure to lighting strikes. People in landslide prone areas should be on high alert. Updates will be provided promptly if there are any changes.
Message Addressed to:	Cabinet Secretary, Ministry of Environment and Forestry, Chief Administrative Secretary, Ministry of Environment and Forestry; Principal Secretary Ministry of Environment and Forestry; the Presidency; Government Spokesman; National Intelligence Service, Kenya Red Cross, Kenya Maritime Authority, Kenya Ports Authority, National Disaster Operations Centre, Media, Relevant Government Ministries, Council of Governors, County Directors of Meteorological Services.
Originator:	For: Director, Kenya Meteorological Department.

FIGURE 6 Example KMD Heavy Rainfall Advisory issued on 14th September 2021 highlighting areas/regions expected to receive more than 20 mm of rainfall in a 24-h period, concerned areas and intended recipients of the EW information (i.e., government and humanitarian organisations)

hydrometeorological monitoring stations for the whole country (ii) A scoping of FldEWS design, which identified the MIKE Hydro Basin hydrological model as a suitable platform given its existing configuration for water resources management purposes under KWSCRP. Testing of the MIKE model system in forecast mode was then taken forward under the Strengthening Early Response Capacity (StERC) project (Section 2.4.2).

2.4.2 | Strengthening Early Response Capacity Project

Kenya Red Cross Society (KRCS) and British Red Cross (BRC) with funding from European Civil Humanitarian Organisation (ECHO) implemented a 2-year project (2019–2020) to enhance flood preparedness for effective flood early action and response in Garissa, Tana River and Kilifi counties located in Tana and Athi basins. This project was known as Strengthening Early Response Capacity (StERC) and provided a synergistic complement to the advances of the KWSCRP (Section 2.4.1). As such, StERC focussed on the flood-prone Tana and Athi river basins covering the counties of Garissa, Tana River and Kilifi (Figure 2) which previously did not have a functional FldEWS. The aim was to improve flood early warning and preparedness capacities in respective county government institutions, partners and communities, through:

- Supporting development and testing of the MIKE Hydro Basin model (at lumped sub-basin scale) to provide 3-day lead time forecasts. The MIKE model is initialised using observed rainfall and driven by precipitation forecasts from KMD out to a 3-day lead time. At the time of writing this paper, the MIKE forecast model for river flow was not yet fully operational.
- Co-development of county flood risk data, dashboards and maps.
- Development of county-specific Early Action Protocols (EAPs) that spell out what actions will be taken based on flood forecast information (including from the MIKE model system), which we consider in more detail in Section 3.3.2. Implementation of these county-specific EAPs is dependent on the county-level institutional capacities and funding mechanisms.
- Supporting the wider enabling context through the improvement of relevant DRM laws and policies in the three most flood-prone counties (Garissa, Tana River and Kilifi) to include components of preparedness, funding and comprehensive disaster management structures to the lowest administration level.
- Establishment of Emergency Operations Centre (EOCs) in Garissa, Tana Athi and Kilifi counties. These will act as disaster coordination hubs with the responsibility for collecting and collating county impact data, drawing on reports held by village administrators, and integrating these data into the county-specific dashboards.

2.4.3 | Kenya Red Cross Society flood Early Action Protocol

Over the recent years, the International Federation of the Red Cross and the Red Crescent (IFRC) has developed the Forecast based Finance (FbF) initiative to drive a ‘paradigm shift’ in humanitarian disaster relief interventions from a ‘responsive’ (acting post-disaster) to a ‘anticipatory’ modality, in which forecasts trigger preparedness actions to mitigate disaster impacts. National Red Cross Societies around the world are now developing national Early Action Protocols (EAPs) for different hazards including floods. EAPs are Standard Operating Procedures (SOPs) that contain pre-agreed; forecast triggers, a set of early actions and associated funding mechanisms (IFRC, 2022). Such finance includes the IFRC's Disaster Relief Emergency Fund (DREF), but EAPs seek to establish cross-sectoral, cross-agency agreements and financing for forecast-based action.

In 2021, The Kenya Red Cross Society (KRCS) completed the development of a national flood EAP [supported through the Ikea foundation Innovative Approaches to Response and Preparedness (IARP)] project. The flood EAP focused on three priority basins of the Tana River, Athi and Nzoia. Consistent with the components of the WMO MHEWS (Figure 1) and the FbF approach this involved:

- Detailed risk assessment, based on collated historical impacts and KRCS disaster response experience (see Section 3.1)
- Identification of longer lead time (sub-seasonal to seasonal, e.g., 30-day lead time) river flow forecast triggers, based on the Global Flood Awareness System (GloFAS) forecasts (see Section 3.2.2).
- Specification of associated early actions to mitigate flood impacts (Table S1 and Section 3.3.2).

Conceptually, EAPs funding mechanism by Disaster Relief Emergency Fund (DREF) is targeted for a high probability of occurrence of flood and other hazards with at least 5-year return period and is likely to affect at least 2000 households (IFRC, 2022). For Kenya, these factors were considered during the development of flood EAP before approval. The flood EAP in Kenya is implemented in a two-step process: the pre-activation and actual activation process once the pre-agreed triggers are reached based on defined GloFAS forecasts (Section 3.2.2) thresholds for each basin (Nzoia, Tana and Athi). The pre-activation step will be initiated based on when the WRF model rainfall forecasts from KMD and/or Centre (ICPAC) indicate that more than 150 mm of rainfall will be received within an upcoming 10-day or 7-day period. The rainfall threshold is based on the severe weather exceeding a threshold of 50 mm in 24 h, as developed by the WMO Severe Weather Forecasting Demonstration Project (SWFDP) in Eastern Africa, and the ICPAC definition of heavy rainfall over a 10-day period.

In preparation for the EAP activation, and upon reaching the trigger based on GloFAS flood forecast with a lead time of 7 days, the flood EAP will be activated and the activities presented in S1 are implemented. The KRCS EAP development required a technical working group composed of KMD, WRA, other government and non-governmental disaster management agencies, researchers and other key stakeholders. Agreements and Memorandum of Understanding (MoU) were also drawn between KRCS and these agencies to ensure effective operationalization and sustainability of the EAP.

2.4.4 | Other research projects and efforts of note addressing MHEWS in general

There are several active applied research initiatives that are crucial to enhancing flood early warning in Kenya and the surrounding region, including regional and continental scales. We highlight several extensive research initiatives that have received funding from the UK's Foreign Commonwealth and Development Office (FCDO), as well as regional (IGAD) and continental activities (Africa).

Towards Forecast-based Preparedness Action (ForPac, www.forpac.org) and HyFlood for Preparedness Action (HyPAc), which are briefly discussed in Section 3.2.3, are two of the major research projects funded by the UK Science for Humanitarian Emergencies and Resilience Programme (SHEAR, http://www.shear.org.uk/about/home.html), as well as the Africa-SWIFT project, which was funded by the UK (GCRF).

A framework for MHEWS is intended to be implemented at the continental level by the African Union Commission (AUC) with assistance from the United Nations Office for Disaster Risk Reduction (UNDRR). The framework establishes a chain of accountability to ensure the EWS is operational, starting with data collection, progressing to the formation of early warning messages and culminating in the activation of prevention and mitigation measures, which are essential for saving lives and minimising disaster loss and damage. The African Union has had this as a goal ever since the Programme of Action for the Implementation of the Africa Regional Strategy (2006–2015) for Disaster Risk Reduction was adopted (UNISDR, 2015a). Finally, the KMD has participated in the WMO sub-seasonal to seasonal (S2S) real-time pilot project at the national level, whose flood risk data has influenced humanitarian early response (WMO-S2S, 2022).

2.5 | Critical gaps in the current FldEWS

2.5.1 | Flood risk knowledge

Despite recent improvements in FldEWS's expansion to other key flood-prone basins (discussed in Section 2.1), historical flood risk data for many basins across the country is nevertheless inadequate and we note the following that:

i. There remains no unified national flood inundation return period database for all the flood-prone areas identified in National Water Master Plan (2030; Figure 2). In Sections 3.2.3 and 3.2.4, we describe exemplary modelling approaches in both riverine floodplain and urban contexts that could address this gap.
ii. Information on the other components which determine flood risk, namely the vulnerability and exposure is limited and fragmented where available (Weingärtner et al., 2019). There is no national database for flood impacts and vulnerability/exposure. Demographic data is held by different institutions at different administration levels and is collected under varying protocols. At a national level demographic data is managed by the Kenya National Bureau of Statistics (KNBS) based on census surveys every 10 years, but at varying spatial resolution due to changing governance systems and administrative boundaries over time. At sub-national level this data is held by administrators, collecting data using protocols that differ from that of KNBS. It is indeed a major challenge to obtain data at sufficiently high resolution to inform flood risk. We describe efforts to that end for basin scale analyses in Section 3.1 and at the local level in urban areas in Section 3.2.4.
iii. There exist no nationwide centralised and comprehensive database of historical flood impacts. Such data as do exist are held by various government and humanitarian agencies. There is no unified data collection system and protocols; for example, most data entries do not record flood economic losses. There are also no clear data-sharing frameworks between institutions and administrative levels. In Section 3.1, we highlight the efforts by KRCS and other partners to harmonise such data.

2.5.2 | Flood monitoring and forecasting

Monitoring: Despite recent investments (notably through the KWSCRP discussed in sections 2.2 in 2.4.1), Kenya currently has a relatively limited network of hydrometeorological stations outside the Nzoia river basin, largely due to high investment and operational costs, limited capacity for maintenance and slow technological uptake (Shilenje & Ogwang, 2015).

Forecasting: The Nzoia FldEWS remains the only currently operational system, although there are very promising initiatives in the Tana and Athi basins that should be fully developed. While the Nzoia FldEWS has operated effectively for many years and recently undergone improvements there is still a clear gap in Kenya's capability to predict flood events across the flood-prone areas. Furthermore, the operational Nzoia FldEWS itself has limitations which we highlight as follows:

i. The flood forecasts (and indeed those from the proposed Athi and Tana river forecast systems) have a relatively short lead time (up to 3 days) in which the main input is the 72-h precipitation forecasts from KMD WRF model.
ii. Flood forecasts are deterministic in nature, rather than probabilistic, due to lack of capacity (computational and technical) to run ensemble flood forecasts.
iii. Forecasts are provided for river levels only and not the expected flood inundation areas which limit the utility for preparedness actions and hinders a shift towards impact-based flood forecasts as recommended by the WMO (WMO, 2015). In Section 3.2, we present some of the advances that have the potential to address gaps in flood forecasting.

2.5.3 | Forecast warning communication, preparedness actions and monitoring and evaluation of socio-economic benefits

The Nzoia river FldEWS has a well-developed system of communication via various channels (see Section 2.2.2). Nevertheless, in recent flood events an estimated 40,000 people were displaced by floods and emergency evacuations were conducted (FloodList, 2020; Marsham, 2020). There is a need therefore for continuous monitoring and evaluation of the efficacy of the system.

As FldEWS are extended to other basins, there is a clear need to implement effective warning communication and preparedness actions. In this paper, our emphasis is on preparedness actions activated by risk management agencies rather than populations at risk themselves, as the latter typically requires support from the former. In this context, preparedness and effective response is likely to be hampered by overlapping mandates and limited coordination amongst multiple disaster risk management agencies across administrative levels. Unlike drought risk management, flood risk management in Kenya does not have harmonised policy, funding, and management structures at national and county levels. As such, at national and county level flood risk management protocols and contingency planning remain inadequate in most cases. In the absence of such guidelines, flood risk management in Kenya remains rather ad hoc. Similarly, the lack of a national FldEWS and guidelines/protocols exacerbates the flood risk management in Kenya. In Section 3.3, we turn and discuss in detail some of the advances that have been made towards addressing these challenges.

3 | INNOVATIONS, ADVANCES AND OPPORTUNITIES TO ADDRESS THE PRIORITY GAPS

Here we present new research that addresses these priority gaps and have potential to improve FldEWS in Kenya. The research emerges from the new initiatives noted in Section 2.5 and other complementary activities and research.

3.1 | Disaster risk knowledge

In developing flood EAPs, KRCS developed a nationwide flood risk database, which extends beyond the detailed analysis being conducted by WRA (Section 2.2.1). The fragmentation of flood risk data (Section 2.4.3) required KRCS to undertake the collation, harmonisation and analysis of hazard, exposure and vulnerability data across the country. Flood extent return period maps, derived from model simulations, were obtained using ERA-Interim (ERA-I) reanalysis streamflow data obtained from the European Centre for Medium Range Weather Forecasts (ECMWF; Pappenberger et al., 2012). Coupling land surface model coupled with the ERA-Interim reanalysis meteorological forcing (1979–2010) resulted in a runoff which was then passed to a river routing algorithm. The discharge data from ERA-I were then converted into river level and fitted with Gumbel Extreme Value Distribution to provide flood inundation maps for varying return periods (i.e. 5, 10, 20, 25-year return period maps) for Tana, Nzoia and Athi River basins (and indeed for the whole countrty) at 1 km grid resolution. The rather coarse resolution flood maps were deemed sufficient for the purpose of flood risk mapping at ward administrative level in the development of the flood EAP. Note that flood inundation return period maps at much higher resolution (30 m) are being developed (Section 3.2.3).

Flood impact data were drawn from various sources including international archives, specifically: EM-DAT from the Centre for Research on the Epidemiology of Disasters (CRED); The Disaster Inventory System (DesInventar) of UNDRR; National archives, that is, KRCS's Emergency Operations Centres (EOCs), National

Drought Management Authority (NDMA); Media reports and various institutional reports. Data on vulnerability, exposure and coping capacity indicators were obtained from the KNBS integrated household budget surveys and the 2019 national population census. Relevant vulnerability information includes vulnerable population numbers (ie. those above 65 and below 5 years), housing construction, transport access, sanitation conditions and healthcare access, while coping capacity is determined by unemployment rate, sanitation conditions, access to urban centres and access to early warning system (Otieno et al., 2019).

The vulnerability and exposure data were then aggregated to obtain an integrated risk score using the method of the Index for Risk Management (https://drmkc.jrc.ec.europa.eu/inform-index) down to the ward level (see an example for Nzoia River basin flood risk map in Figure 7 and for Tana and Athi in Figures S1 and S2). KRCS and technical support from an initiative Netherland's Red Cross global 510 teams (based at the Netherlands Red Cross) created a community risk dashboard (Rode Kruis Dashboards, 2022) with institutional agreements and MoUs to ensure ongoing sustainable provision of flood risk data.

Using the Index For Risk Management (INFORM) approach, a community risk assessment (CRA) approach was developed by the KRCS to highlight the most vulnerable communities, the underlying conditions that make them vulnerable to flood hazard, their coping capacity and whether these communities are exposed to flood hazards or not (Groeve et al., 2014). To delineate communities at high risk of floods a combination of data on vulnerability, flood exposure and lack of coping capacity was used to develop flood risk index (see Figure 7 for Nzoia River Basin). Integrating analysis from rainfall forecasts with information generated from the flood community risk assessment enables the population at high risk to act ahead of impending flood events. Components for the flood CRA were obtained from the Kenya national bureau of statistics (KNBS). These components are grouped and weighted within the three INFORM dimensions to give a flood risk score as presented in Equation 2 (Otieno et al., 2019).

$$\text{Flood risk score} = \text{Vulnerability} \times \text{Flood exposure} \times \text{Lack of coping capacity} \quad (2)$$

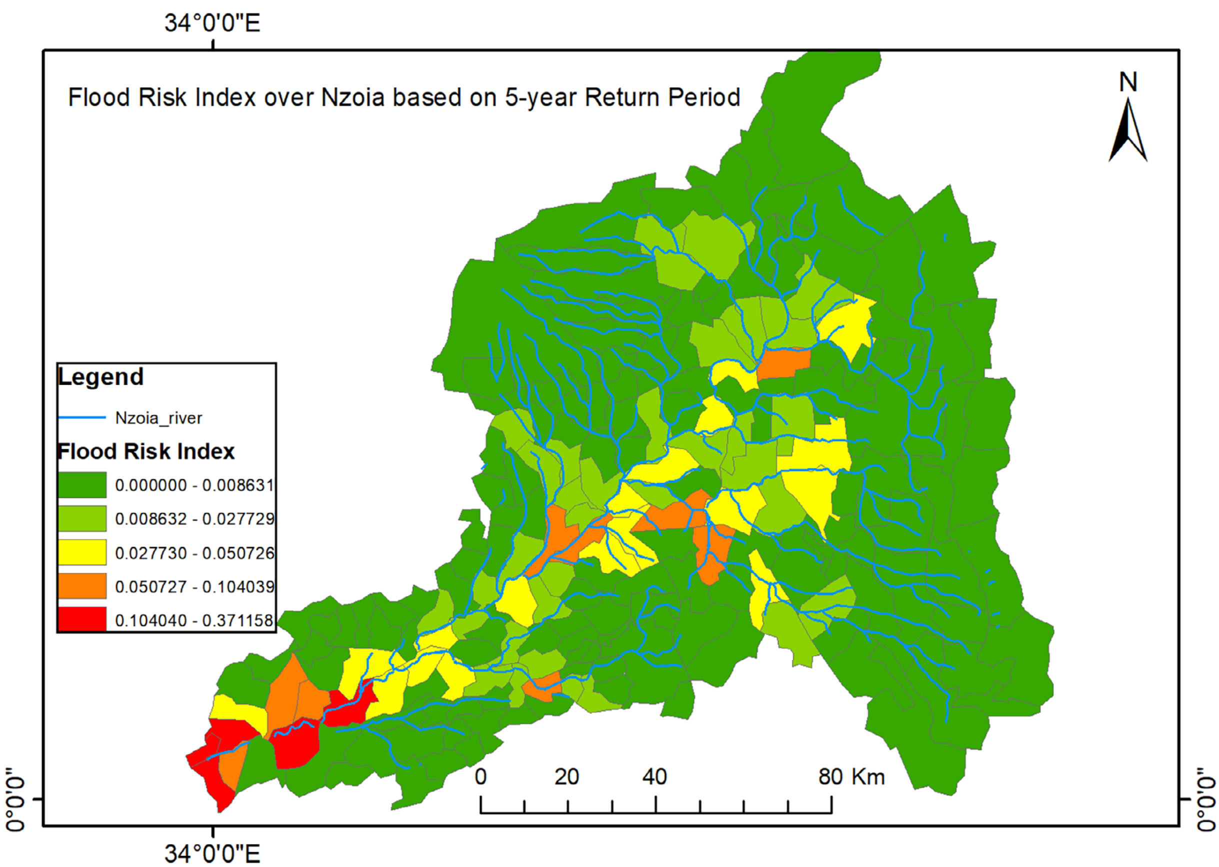

FIGURE 7 An example of flood risk map modified from KRCS flood risk data and available from the Red Cross Dashboard, in this case for the Nzoia Rivers. The risk score shown is derived using the INFORM methodology merging data on hazard, specifically the 5-year return period maps, vulnerability, exposure and coping capacity. The location of the Nzoia river basin is provided in the insert and in Figure 2

3.2 | Improving meteorological and hydrological forecasting

3.2.1 | Improved rainfall forecasting

Accurate rainfall forecasts are a crucial requirement for flood forecasts. In this section, we briefly consider advances across forecast lead times. 'Nowcasting' predictions for the next few hours are based on high-frequency geostationary satellites (ground-based weather radar are typically not available in Africa). The Eumetsat Nowcasting Satellite Applications Facility (NWC-SAF) provides a suite of products, including convective rainfall from large convective systems which typically deliver heavy rainfall in Kenya (and indeed across tropical Africa). These are provided to National Meteorological Services through the Preparation for the Use of Meteosat in Africa (PUMA) software systems. Until recently, however, these systems have been hardly used in tropical Africa (Parker et al., 2022), but projects are addressing this gap by enhancing nowcasting capacity at various National Meteorological Services in Africa, for example, SWIFT and the High Impact Weather Lake System (HIGHWAY) project (https://public.wmo.int/en/projects/high-impact-weather-lake-system-highway-project; Parker et al., 2022; R. D. Roberts et al., 2022). Currently in Kenya, NWC-SAF is accessed by KMD via the NCAS-SWIFT online catalogue and is used for tracking the path and severity of developing storms in generating more accurate high impact, short-range weather forecasts (A. J. Roberts et al., 2021). There exists potential for greater use of these nowcasting forecasts in short-lead flood forecasting, for example, in the context of urban flood forecasting (Section 3.2.4).

At traditional weather forecast timescales (of a few days ahead), recent analysis demonstrated that the accuracy of rainfall predictions is low for Africa (Vogel et al., 2018). This sobering result likely places limits on the skill of short-range hydrological forecasts driven by such rainfall forecasts, including forecasts from the KMD WRF regional forecast model that is currently used to drive the Nzoia FldEWS. Errors introduced by convective parameterizations are the key constraint on forecast skill. Such errors are unavoidable when models are run at resolutions larger than the spatial scale of typical convection. However, a new generation of high spatial resolution convection-permitting forecast models is emerging, such as the UK Met Office Tropical East Africa Convection Permitting ensemble model (CP-ENS), running at 4 km, and these have shown improved forecast skill over East Africa (Cafaro et al., 2021). Rainfall forecasts from these systems offer a strong hope for improving short-range flood forecasts and the utility of CP-ENS rainfall forecasts to drive the Nzoia river FldEWS was assessed over a short period during the SWIFT project testbed in 2020, but there is a clear need to extend this hydrological forecast evaluation to other flood-prone basins.

Forecasts of rainfall at longer sub-seasonal lead times (extending out to a few weeks ahead) are receiving increasing attention, substantially on the basis that in the latest global models, the predictability of the Madden–Julian Oscillation (MJO) has improved (Vitart, 2017). Recent study highlights East Africa as a 'sweet spot' of rainfall predictability at sub-seasonal scales across both the long and short rainy seasons (Macleod, Dankers, et al., 2021) suggesting a clear opportunity for utilising such forecasts in longer lead time flood forecasting. Currently, most African NHMS, including KMD, do not provide such forecasts (Kolstad et al., 2021), although this is being addressed under the WMO S2S real-time pilot project (Hirons et al., 2021).

Seasonal-scale rainfall forecasts have a much longer history of application in Africa. Since 1998, the East Africa the Greater Horn of Africa Regional Climate Outlook Forum (GHACOF), has provided season-ahead outlooks of seasonal rainfall and since 2019 these are based on an objective multi-model approach (https://icpac.medium.com/improved-seasonal-forecast-for-eastern-africa-57872645f449) using forecasts from the GPC models (available through Copernicus, https://climate.copernicus.eu/seasonal-forecasts and the North American Multi-Model Ensemble, https://www.cpc.ncep.noaa.gov/products/NMME/). Such forecasts typically provide only rather coarse-grained information, for example, the probability of total rainfall in the coming season being within three broad 'tercile' categories (i.e., 'below normal', 'normal' and 'above normal'). Nevertheless, much of East Africa is relatively unusual in showing some correlation between seasonal totals and the degree of flooding, at least in part related to aridity (Stephens et al., 2015). However, there is a marked disparity in predictability between the two major rainfall seasons over East Africa, with the short rains (October–December) exhibiting high predictability to the strong influence of the Indian Ocean Dipole and El Niño Southern (Berhane et al., 2014; Black, 2005; Indeje et al., 2000), in contrast to the long rains (March–May) for which consistent and strong drivers remain elusive (MacLeod, 2019). However, there is some evidence that the pattern of anthropogenic warming in the Indo-Pacific oceans is leading to increasing predictability of long rains drought (Funk et al., 2019). The implication of this emerging relationship for flood prediction remains unexplored. Recently, under the UK WISER programme (https://www.metoffice.gov.uk/about-us/what/working-with-other-organisations/international/projects/wiser) the Strengthening Climate Information Partnerships—East Africa (SCIPEA) project supported the development of seasonal hydrological flow forecasts for the short rains by KMD, with the UK Met Office to inform reservoir operations to optimise electricity generating capacity by KenGen, Kenya's largest electricity supplier (WISER, 2020). Such an approach could in principle be extended to seasonal flood risk forecasts co-produced with flood risk management agencies.

3.2.2 | Flood forecasting from the global flood awareness system

Advances in sub-seasonal to seasonal forecasting (S2S; Section 3.2.1), provide an opportunity for extending the lead time of hydrological forecasts. The Global Flood Awareness System (GloFAS), is one such hydrological forecast system, jointly developed by ECMWF and the Joint Research Centre (JRC; Alfieri et al., 2012). GloFAS consists of a distributed LISFLOOD hydrological model at 10 km grid resolution (van der Knijff et al., 2008), initialised and driven by ECMWF sub-seasonal (and seasonal) forecasts. The system provides 51-member ensemble forecasts of river discharge for medium (those with greater than 30,000 km^2) and large river basins globally (e.g., Amazon River with 7 million km^2; Thielen et al., 2012) with long lead times out to 46 days (and 90 days in seasonal mode; https://www.globalfloods.eu/glofas-forecasting/). This forecast system provides an ensemble of daily river discharge across a global river network at 0.1° resolution (Alfieri et al., 2013; Hirpa et al., 2018; Zsoter et al., 2020). To detect the likelihood of high flow situations, for forecasting flood events, the real-time river discharge ensemble forecasts are compared with a set of flood thresholds derived from a 39-year (1980–2018) long climatological simulation, a daily river discharge reanalysis time series (Alfieri et al., 2020). GloFAS forecasts have been applied successfully in the National Red Cross Societies EAPs in Kenya and elsewhere globally including Uganda, Bangladesh, Ethiopia, Pakistan and Niger to trigger an early action on floods (de Perez et al., 2016; Passerotti et al., 2020).

For any operational application, a comprehensive skill assessment of GloFAS is therefore necessary and initial results for some locations are promising (Bischiniotis et al., 2019; de Perez et al., 2016; Passerotti et al., 2020). In this article, we present part of our results (comprehensive GloFAS skill assessment ongoing, Kiptum 2022 personal communication) as an illustrative skill assessment of GloFAS for the Tana and Nzoia river basins in Kenya. We compare GloFAS reforecasts for the period 1999–2018 against the daily river flow records for the Tana River basin (at Garissa town; 39.55° E, 0.35° S, shown in Figure 2) and Nzoia (at Rwambwa Bridge; 34.25° E, 0.15° N, shown in Figure 5). First, we defined a 2-year return period as a threshold to represent flood 'events' in the two basins by fitting a Generalised Extreme Value (GEV) distribution (Gumbel, 1958) to the annual maximum values of the observed river flow records for Tana at Garissa (4G01) and Nzoia river Basin at Rwambwa bridge (1EE01).

Flood events in the GloFAS reforecast data were then defined when there is at least a 50% probability, across the GloFAS reforecasts ensemble, of exceeding the observed 2-year return period threshold value. Further, for verification we apply a flood anticipation 'window': that is, we do not demand that forecasted flood events occur on the same day as the observed event, but rather within some 'window' following the forecasted event (de Perez et al., 2016) and in this case we use a window of 20 days. This is appropriate because in practice any flood preparedness actions triggered by a flood forecast have a 'lifetime' in that they remain valid even if the flood event occurs sometime after the forecasted flood event (de Perez et al., 2016). This will obviously depend on the type of action: prepositioning non-perishable supplies will have a long 'window', and evacuation of people will have a short window. On this basis, contingency tables were then derived for 'hits', 'misses', 'false alarms' and 'correct negatives'. We focus on two of the more decision-relevant skill indicators, namely the False Alarm Ratio [FAR, Equation 3 and Probability of Detection (POD), Equation 4], derived for each forecast lead time (Figure 8).

$$\text{False Alarm Ratio}\,(FAR) = \frac{\text{False alarms}}{\text{Hits} + \text{False alarms}} \tag{3}$$

$$\text{Probability Of Detection}\,(\text{POD}) = \frac{\text{Hits}}{\text{Hits} + \text{Misses}} \tag{4}$$

For the Tana River Basin (Figure 8a), results suggests potentially useful forecast skill at extended lead times out to almost 20 days, with FAR values lower than the Red Cross definition of tolerable FAR of 50% (de Perez et al., 2016). We also note that, although GloFAS skill verification scores for Nzoia River Basin (Figure 8b) suggest high POD values (>50% up to around 20-day lead times), there is also a high FAR value (>50% across all the lead times) which might not be tolerable for humanitarian actions. Skill at short lead times of a few days is

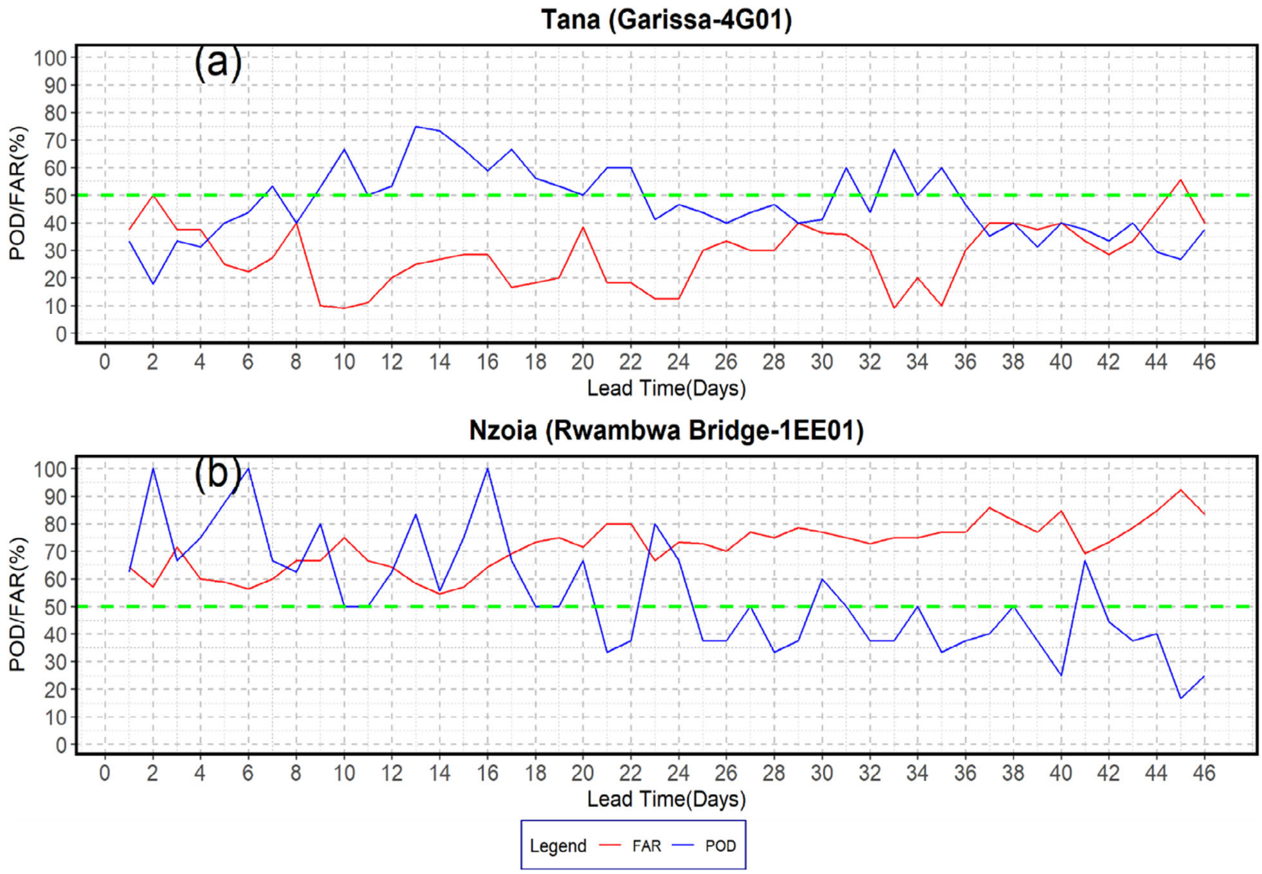

FIGURE 8 Illustrative skill assessment (False Alarm Ratio and Probability of Detection) for GloFAS flow forecasts of a 2-year return period threshold of flow using a 50% trigger probability over (a) Tana at Garissa station and (b) Nzoia River. Green horizontal dashed line indicates a 50% tolerable FAR threshold

also quite low, and it is not yet clear to what extent this is due to lower skill of short lead ECMWF rainfall forecasts (Vogel et al., 2020) or LISFLOOD initialisation biases. Note that skill statistics degrade for shorter anticipation window durations and higher return period thresholds notably 5-year return period (Figure S3). Further, the tolerable FAR will of course vary depending on the stakeholder priorities and the preparedness action costs and efficacy, highlighting the need for thorough engagement and between forecast providers and risk management decision-makers, through the co-production process (Hirons et al., 2021).

Hindcast skill may improve further if future GloFAS model calibration could incorporate stations over Kenya as we also noted no station in Kenya was included during the recent GLoFAS calibration exercise (Hirpa et al., 2018). Nevertheless, there is clearly potential for GloFAS to be utilised for anticipatory action up to several weeks in advance. This could complement the shorter flood forecast lead times from current and planned basin flood forecasting operated by the Kenya-mandated agencies of KMD and WRA.

3.2.3 | Prototype coupled flow and flood inundation forecasting

Flood risk management is much better informed by forecasts of the extent of actual flood inundation, rather than river flow forecasts. To this end, the HyPac project (funded by the UK SHEAR programme) aims to assess the potential for inundation forecasting by coupling ensemble river flow forecasting from GloFAS (Section 3.2.2) with flood risk maps derived from the Fathom Global Flood Model (GFM; Sampson et al., 2015).This GFM hydraulic model simulates riverine flooding globally in two-dimensional at a 3-arc second (~90 m) resolution for all river basins with an upstream catchment area >50 km^2. The modelling framework used to create the inundation maps utilises a sub-grid channel hydrodynamic model within LISFLOOD-FP (Neal et al., 2012) to explicitly represent the river channels.

Boundary conditions for the model are taken from a regionalised flood frequency analysis conducted at a global scale (Smith et al., 2015), linking river discharge and rainfall measurements in gauged catchments to

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ungauged catchments by upstream catchment characteristics and climatological indicators. The version of the GFM used in this study differs from the Sampson et al. (2015) version in so far as topography information stems from the MERIT DEM (Yamazaki et al., 2017) and the river network from MERIT-Hydro at a spatial of 3-arc resolution (~90 m at the equator; Yamazaki et al., 2019), respectively, the best global terrain and hydrography data currently available. Thus, the GFM used here may be considered the latest state-of-the-art GFM. Simulations were conducted by flood return period (RP) (for 5, 10, 20, 50, 75, 100, 200, 250, 500 and 1000 years flood events). Figure 9 provides an illustration of a 1 in 100-year return period flood inundation map derived for the Nzoia River Basin.

In the Kenyan context, these flood simulations can make crucial contributions to the development of FldEWS. First, the simulations can be utilised in historical flood risk assessment by combining them with exposure and vulnerability datasets (Component 1 of Figure 1). This may be especially useful given the absence of detailed flood RP inundation maps (Sections 2.2.1 and 2.5.1). Note that these new flood inundation RP maps are at considerably higher resolution than those used by KRCS in Section 3.1 (30 m vs. 1 km). Second, in forecasting inundation (Component 2 of Figure 1), the flood RP inundation maps can be used as a 'library' of pre-simulated flood impact scenarios that can be 'sampled' based on the probability of river flow forecast exceeding a particular RP, as illustrated in Figure. For example, if a river flow forecast (e.g., from GloFAS) indicates that the 5-year RP will be exceeded, then the 5-year inundation simulation map would give an indication of the areas expected to be inundated (Figure 10). This method can generate forecasts of flood inundation and impact when combined with exposure and vulnerability information (Figure 7) without the computational burden of operationally running the inundation model in real time. This approach is consistent with systems such as the European Flood Awareness System (EFAS, https://www.efas.eu/en/european-flood-awareness-system-efas). The HyFlood project is evaluating integration of these new flood inundation RP maps with GloFAS flow forecasts to provide a probabilistic forecast of flood inundation at 30 m spatial resolution. Of course, the potential exists to use the even higher resolution flood RP maps generated by WRA where available (Section 2.2.1).

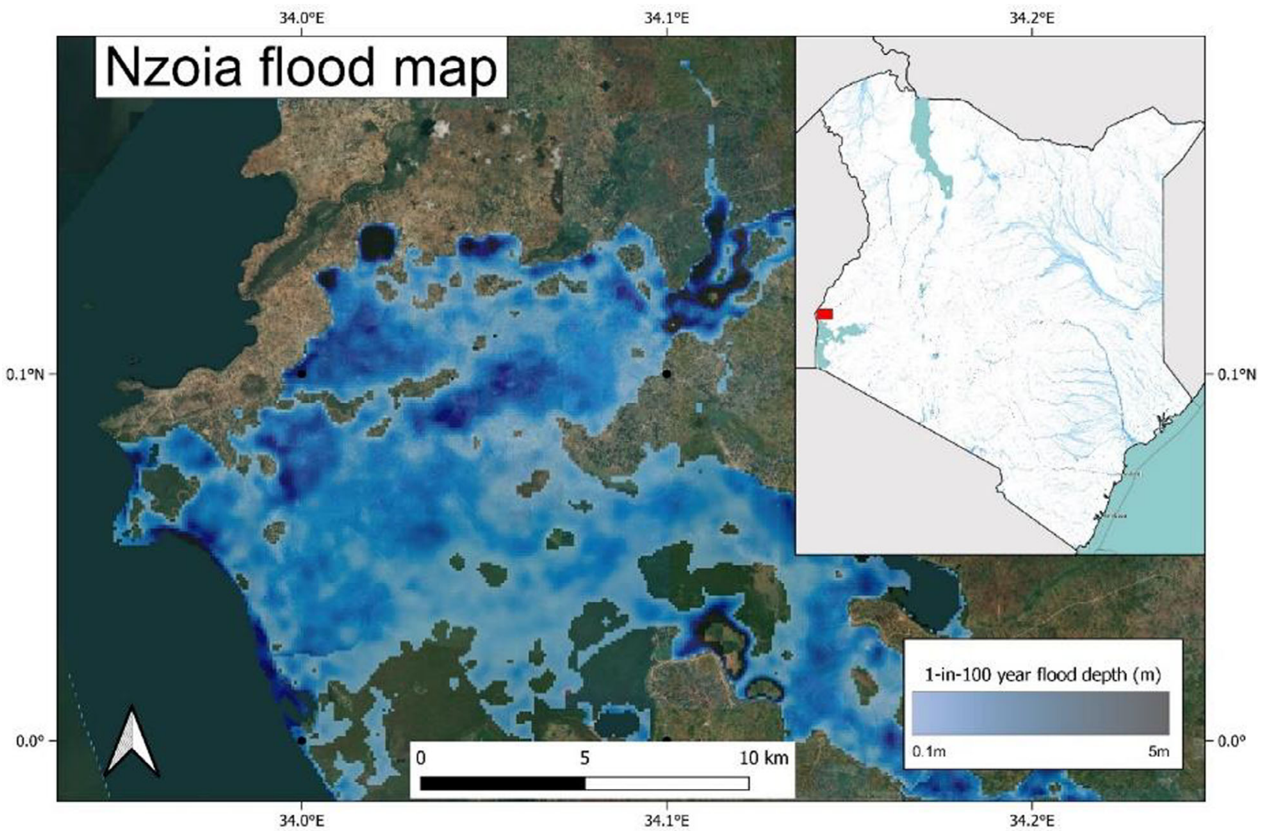

FIGURE 9 1-in-100-year return period flood map for Nzoia, Kenya derived using the Fathom GFM model under the SHEAR HyPAc project

3.2.4 | Potential for flood forecasting in urban contexts in Kenya

Kenya, like much of Africa, is experiencing rapid and often poorly planned urbanisation (Lumbroso, 2020) which increases flood risk (Di Baldassarre et al., 2010) such that many urban centres in Africa are now regarded as flood disaster risk hotspots (Baker, 2012). Nairobi's population of around 5 million is growing at 4%–5% per annum, with almost 75% of this growth absorbed by informal settlements of high density with poor drainage systems and mainly situated in low-lying areas along riverbanks (Sen, 2020). The city suffers from pluvial and fluvial floods caused by heavy rainfall, exacerbated by blocked drainage systems and encroachment of development into the floodplains, with resulting loss of lives, destruction of property and disrupted critical services such as transport and power supply (Quagliolo et al., 2021) and outbreaks of water and vector-borne diseases and can interact with a range of other hazards (Malamud et al., 2021). The impacts are more severe in informal settlements due to higher exposure and vulnerability (KDI, 2022). With risk growing, there is a pressing need for improved flood forecasting and risk mapping as part of a wider flood mitigation strategy which is to support the Nairobi city county government which is currently developing a disaster risk management plan.

There are no direct flood forecasts for the City/county aside from the KMD HRA (Section 2.3.2). Flood forecasting could take advantage of Nowcasting and/or NWP forecasts (ideally ensemble forecasts) to manage flood preparedness action at these very local scales. A similar initiative is underway for Dakar in Senegal through the SHEAR project 'Nowcasting Flood Impacts of Convective storms in the Sahel' (NFLICS; http://shear.org.uk/research/catalystGrants/NFLICS.html). For certain flood mitigation activities including drainage clearance and maintenance, longer lead time weather and climate forecasts at coarse spatial resolution are probably sufficient to guide early actions. Initiated under the ForPac project KMD is currently providing seasonal and sub-seasonal rainfall forecasts to stakeholders in Nairobi within the city to trigger various flood mitigation actions. These stakeholders include Nairobi City County government (specifically the disaster risk and coordination, environment, roads, transport & infrastructure sectors), Kenya power and lighting company, the Nairobi County Kenya Red Cross branch and community leaders in the informal settlement of Kibera (one of the most flood-prone informal settlements). This latter forecast design and communication initiative are being developed through the DARAJA project (Developing Risk Awareness towards Joint Action) which is trialling flood warnings co-developed with residents of informal settlements in Nairobi and Dar es Salaam, an initiative that has resulted in tangible benefits for residents (Norman, 2018).

Forecasts of heavy rainfall events can be translated into more specific flood inundation warnings. As with basin-scale fluvial flood, the ForPac project is working towards an approach (Figure 10) in which flood forecasts are generated by linking rainfall forecasts/nowcasts with a 'library' of inundation RP maps built from high-resolution hydraulic simulations, thereby avoiding the requirement to run hydrodynamic simulation in real time. Flood inundation is being estimated using the 3Di modelling system (KDI, 2022) a high-resolution hydrodynamic surface water model, from which inundation RP maps are currently being derived (Figure 12). For verification (Figure 11), in the absence of an official archive of flood data for forecast verification the ForPac project compiled an archive of 1500 flooding reports from print and social media for reports for the period between 1975 and 2018.

Looking forward there is a need to develop integrated flood RP maps for both pluvial and fluvial flooding. Existing flood RP maps for fluvial events for the Kibera informal settlement which lies exposed in the Ngong river floodplain area have been derived by KDI using locally derived evidence (Mulligan et al., 2017). Similar participatory flood risk mapping, necessary to provide accurate flood information at the high spatial resolution required in the most densely populated and vulnerable areas, has been undertaken, taking advantage of new data tools like OpenStreetMap (e.g., Gebremedhin et al., 2020).

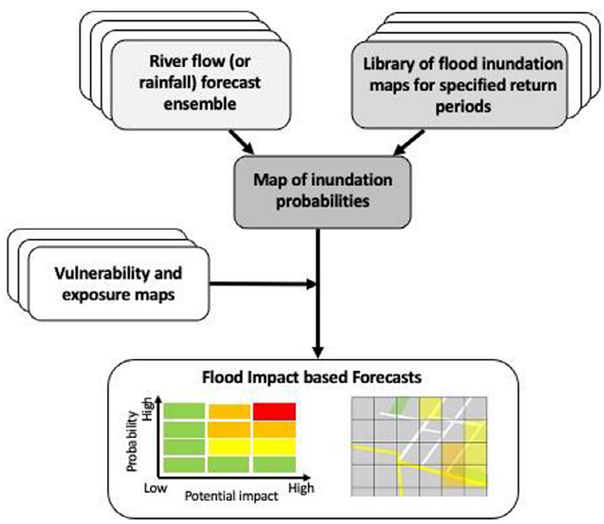

FIGURE 10 Schematic illustration of method for linking ensemble hydro-meteorological forecasts to pre-simulated inundation impact scenarios for surface water flood forecasting (Speight et al., 2021)

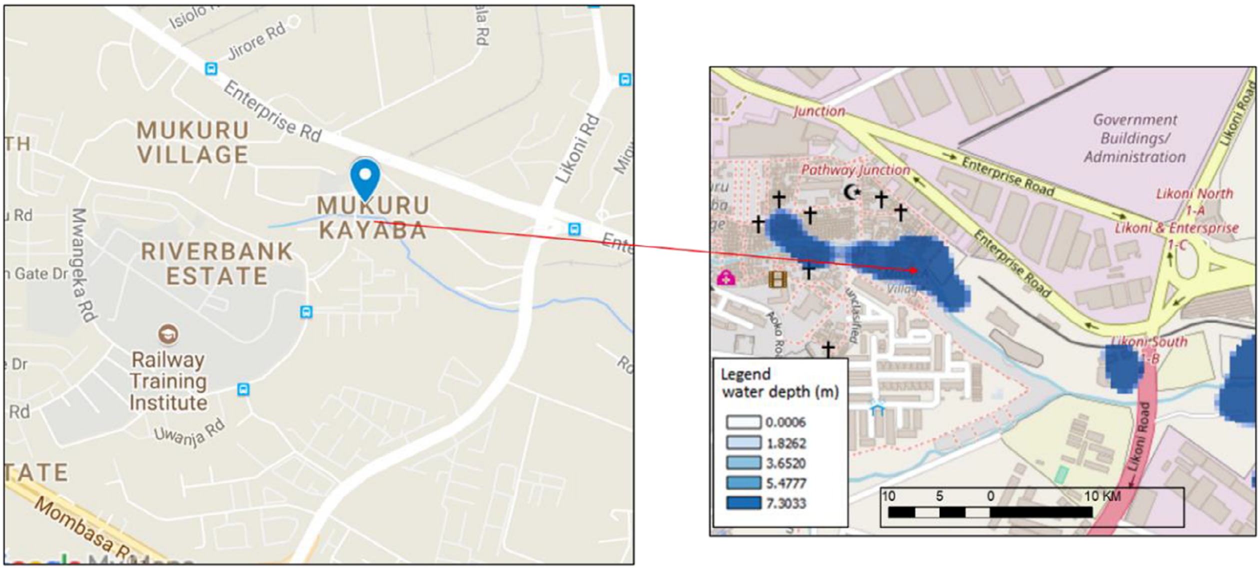

FIGURE 11 Illustration of a flood event map (for 10th November 2015) generated from a high-resolution hydro-dynamic surface water model 3Di for Mukuru Kayaba informal settlement in Nairobi

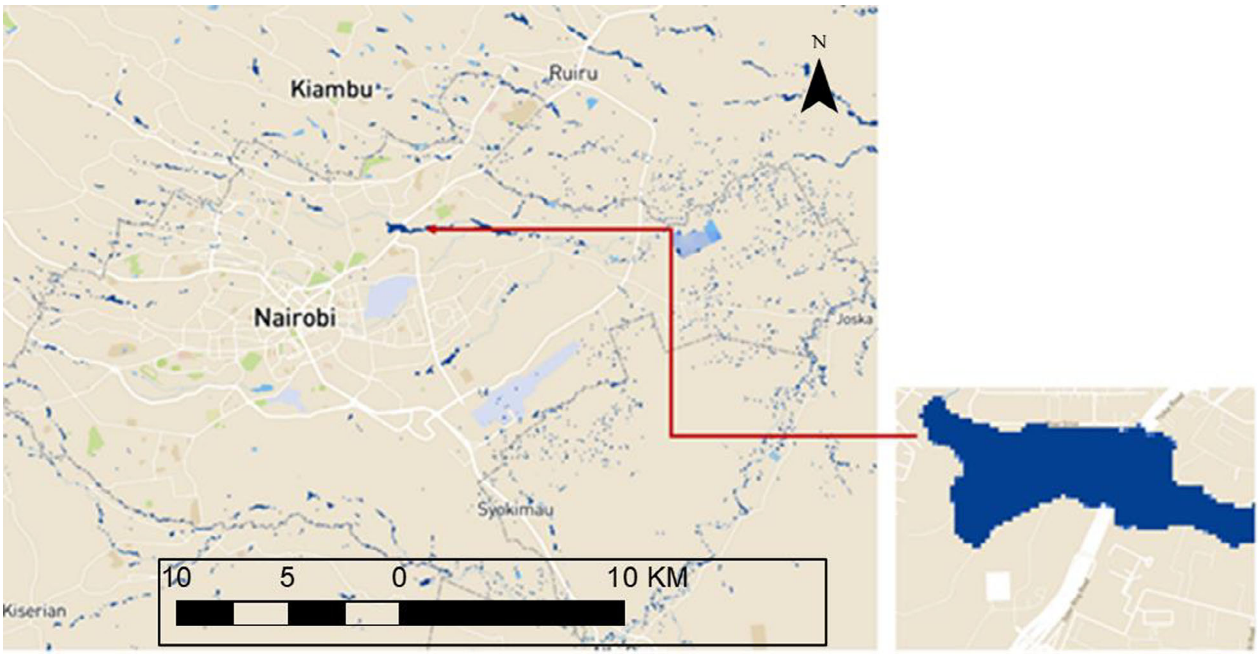

FIGURE 12 An example of a 2-year flood return period map generated using the 3Di model

In summary, we demonstrate the potential for the generation of flood inundation simulations for rainfall and river flow RP benchmarks and provide a framework and methodology by which a real-time flood inundation forecast system might operate. There is a clear need to extend further from this 'proof of concept', and to link this flood risk information into both real-time FldEWS and to long-term planning towards climate resilient cities. Nairobi County Government has prepared a County Disaster Management Act that mandates the Directorate of Disaster Management to prepare a disaster management plan. In addition, the City Government have recently begun engaging various stakeholders through Special Planning Area (SPA) initiatives, aimed at facilitating an integrated approach to disaster risk reduction within informal settlements. As such, there is a window of opportunity for flood risk information and FldEWS to be integrated into disaster risk planning.

3.3 | Lessons in forecast communication and preparedness action from recent projects

3.3.1 | Communication

The lack of effective dissemination and communication of early warning information to those most at risk throughout most of Africa is cited by WMO as a key shortcoming in the value-chain for MHEWS (Lumbroso, 2018; Lumbroso et al., 2016; Onencan et al., 2016). WMO has designed the Common Alerting Protocol (CAP) as a recommended approach for a standard message format designed for communication of warnings for any hazard type across all-media. KMD have adopted the CAP, most notably for the HRA (Figure 6) and flood warnings for the Nzoia river FldEWS (Figure 4). Indeed, Kenya is one of only a few African countries with an operational CAP. Nevertheless, the link between well-disseminated and communicated warnings and subsequent preparedness actions is not always straightforward and depends on many factors. For example, there is evidence from Kenya that a lack of trust in forecast information hinders preparedness amongst at-risk populations in favour of a 'wait and see' approach (Muita et al., 2021). On that basis, we highlight here only some lessons which complement the existing principles and practices of CAP adopted by KMD.

The DARAJA project worked with existing community and radio networks in urban informal settlements in Nairobi to enhance the communication of forecast information. Together with stakeholders they (i) co-designed forecast messaging in more accessible language and formats; (ii) diversified communication channels to extend the reach of warnings through: local radio stations, SMS, social media, word of mouth and a flag system at river crossing points; (iii) co-developed tools to facilitate interpretation and use of the forecasts and such as reference guide for the Climate Information Service (CIS) intermediaries; and (iv) build trust between users and producers of climate information by ensuring regular interaction through in-person forums, radio shows and through WhatsApp groups. As a result, the project reported improvements amongst the community in understanding of early warning information and ability to protect their assets (https://www.resurgence.io/solutions/climate-risk-visualisation-and-communication/daraja/).

At river basin level, the StERC project together with county stakeholders (i) co-designed county-specific communication strategies that would ensure the design of context-specific early warning information, that is, in a format and language that is applicable to each county; (ii) creation of county and grassroot structures for information dissemination and feedback; and (iii) diversification of channels for communication of early warning information. At the time of writing this article, the communication strategies had been adopted by the respective county government but were not fully operational. There is a need to scale these approaches up to other at-risk flood-prone areas to complement the standard office warning systems.

3.3.2 | Preparedness actions

In Kenya, flood risk preparedness and management have been rather ad hoc due to limited coordination amongst risk management agencies and inadequate flood management protocols and contingency planning at national and subnational levels. This complex issue has been addressed by many of the initiatives described in Sections 2 and 3. Most notably the flood EAPs (effectively SOPs) developed under KRCS-led initiatives at the national and county level. We illustrate the preparedness actions below.

i. The KRCS national flood EAP (Section 2.4.3) is designed to improve institutional coordination and provide a framework for flood risk preparedness action guidelines: it spells out which actions (to mitigate flood impacts) should be carried out at what time and by which risk management agency (full details available in Table S1). Currently, these EAPs are specific to forecasts of river flow exceeding the 1- to 5-year return period with trigger probability of 85% probability of exceedance in the GloFAS forecasts at 7-day lead time. EAP also link to specific funding streams such as FbA by the DREF. At the time of writing, KRCS was organising an EAP simulation exercise over Nzoia river basin that would test the efficiency and effectiveness in trigger threshold communication, stakeholder coordination and implementation of actions.
ii. The County-specific flood EAPs co-developed with stakeholders in the three high flood-risk counties (Tana River, Kilifi and Garissa County) in the Tana and Athi basins, through the StERC project (Section 2.4.2). An example extract of the preparedness actions is shown in Table S2. Unlike the national KRCS flood EAP (that operates based on a single forecast lead time), 7-day lead time GLoFAS flood forecast (see Section 2.4.3, Table S1), the county-specific EAPs adopt a staggered approach of implementing early actions based on KMD rainfall and flood forecasts for 'seamless' lead times across the rainy season; seasonal, monthly, HRA and 3-day

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lead time flood forecasts. On this basis, the associated actions triggered by these forecasts take the form of a 'Ready-Set-Go' approach (Bazo et al., 2019). In this, low-cost/low-regret actions can be taken at longer lead times and more costly actions can be taken at shorter lead times when confidence in the forecast is higher. For the Tana River, the final trigger is a deterministic forecast of river flow about the 4 m height threshold at a bridge near Garissa Town such that the target is for more frequent events than the national flood EAP. The county-specific EAPs identify the institutional responsibilities for early actions.

4 | CONCLUSIONS AND RECOMMENDATIONS

Flooding is a major problem in Kenya and the wider region. Risks from flooding are likely to grow with increasing exposure of populations, vulnerability of many poorer sections of society, and the increased frequency of intense storms under climate change. There is a pressing imperative therefore for improved FldEWS for flood-prone areas, and national coordination of such systems. Kenya has made significant strides in enhancing FldEWS in recent years, but substantial gaps remain in coverage and in overarching components of governance, coordination, data sharing and finance. The result is that many people and livelihoods remain insufficiently protected from flood risk. The research described here demonstrates clear opportunities to improve FldEWS and preparedness in Kenya and we draw the following conclusions and recommendations.

First, there is clear potential to improve the quality and extent of flood risk monitoring and mapping. New methods for generating high-resolution inundation return period maps are available, for floodplains and urban contexts. There is a need to establish what is the most appropriate blend of the very high-resolution inundation modelling informed by lidar-derived Digital Elevation Models (DEMs) currently being undertaken by WRA and the lower resolution, but more extensive 'global' flood inundation modelling based on satellite-derived DEMs. New data on vulnerability, exposure and impacts are being developed through WRA, KRCS risk dashboard and through community-level participatory flood mapping in the most vulnerable areas of Nairobi. To continue, develop and extend these activities investment is needed such as that from the KWSCRP. However, there is still a significant gap in hydrometeorological monitoring over most flood-prone areas and a need for continued investment in monitoring infrastructure, data transmission, archiving and sharing. Along with increased investment to support risk monitoring and mapping, we recommend that WRA through their newly established NFMIAC should take a lead in establishing coherent protocols for such data, coordinating across various agencies and initiatives in establishing data sharing agreements. Critically this should include partnerships with counties and with those communities most at flood risk.

Kenya and East Africa are something of a 'sweetspot' for S2S predictability (Macleod, Dankers, et al., 2021): this is becoming increasingly clear and provides considerable potential to support flood forecasting. KMD should be encouraged to provide such forecast information, and the WMO S2S pilot is a step in this direction. At shorter lead times, skill of most existing weather forecast models remains low and presents a fundamental barrier to flood forecasting. However, new high-resolution convection-permitting models offer evidence of greater skill and NMHS should be supported further to access such products operationally and to conduct comprehensive verification. Nowcasting capabilities are also being enhanced and the potential for linking to flood forecasting should be further explored, notably for pluvial flood risk.

Flood forecasting for the most flood-prone basins is being enhanced, notably under the KWSCRP and StERC projects. However, there are several opportunities that can add significant value and ensure synergistic outcomes with other investments. Extended lead time flow forecasts with potentially useful skill are already available from the GloFAS system. Effective use of these forecasts requires careful verification and indeed observed historical flow data should be shared with GloFAS developers to improve model calibration for the key basins. The longer lead times offered by the current GloFAS system could be combined with shorter lead time forecasts from the existing (and developing) FldEWS can support a more comprehensive set of flood preparedness actions, under a 'Ready-Set-Go' framework. In this context, GloFAS forecasts can offer a 'heads up' for early flood preparedness while the shorter lead basin models operated by KMD/WRA can trigger implementation of more 'costly' anticipatory actions.

Hydrological forecasts (whether from global or basin scale models) can be coupled with a library of flood inundation systems such as that which we describe in Section 3.2.3 (e.g., from the LISFLOOD-FP system and high-resolution Digital Elevation Model) could provide a probabilistic flood inundation forecast. Using flood risk information on flood exposure and vulnerability information could be overlaid on such inundation maps to provide the basis for an Impact based Forecasting system for flooding, akin to what is currently available over Europe the European Flood Awareness System (EFAS). Such advances demand the improved historical flood risk data we propose, as well as a commitment to co-production between agencies to ensure appropriate flood-impact functions are determined that are consistent with the priorities of various risk management stakeholders, as noted in the WMO IbF guidelines (WMO, 2015).

In the longer term, the bespoke basin scale models in existing FldEWS can be driven with sub-seasonal rainfall forecasts, where these are to be provided by KMD. Ensemble hydrological forecasting provides a more comprehensive assessment of risk, than does deterministic forecasting, and the opportunity for a risk based or scenario-based approach to preparedness planning and actions.

When forecast skill information is provided, based on hindcast assessment, this can support an informed and rational basis for optimal preparedness actions. This is the case in the development of the KRCS flood EAPs. The skill of all FldEWS should be thoroughly assessed and that information shared with stakeholders to ensure the credibility of forecasts, a critical quality underpinning effective preparedness actions and which has, to date, received insufficient focus. Similarly, there should be comprehensive verification of rainfall forecasts used to drive hydrological models.

In urban areas, the small space/time scales of pluvial flooding and the complexity of urban morphology, including the role of artificial drainage, means that flood forecasting is especially challenging. This spatial scale required pushes beyond the useful limits of predictability in rainfall forecasts. However, there is potential for application of Nowcasting outputs to flood inundation modelling, and lessons can be learned from similar projects elsewhere in Africa (e.g., the SHEAR NFLICS project). Further, degraded spatial resolution rainfall forecasts can still be effectively linked to flood inundation RP maps to provide probabilistic flood forecasts at high spatial detail, but error propagation should be carefully examined (WMO, 2015).

While KMD adopts the WMO CAP protocols, there are still significant gaps in warning communications to reach those at risk of flooding. The StERC and DARAJA initiatives suggest that this gap can be bridged by co-design of communication products, diversification of communication channels, regular monitoring and feedback and collaboration amongst agencies and stakeholders. There is a need to scale-up these lessons while synergizing with the existing platforms, structures and systems to increase in funding into early warning communication.

Regarding preparedness actions, we report significant advances in developing standard operating procedures/plans for flood preparedness in Kenya. Notably, the county and basin flood EAPs pioneered by KRCS provide a framework to guide flood risk preparedness and enhance coordination amongst agencies. For the Tana River basin counties, county-specific EAP is built around a 'Ready-Set-Go' framework involving forecasts at varying lead times, triggering various actions. However, this has only been developed for two basins and is limited to certain agencies. These could usefully be synergized and integrated with other government systems and frameworks for sustainability and buy-in.

Our research also demonstrates that there are several cross-cutting issues that would enhance flood risk management in Kenya. Notably, there is ample evidence presented here and elsewhere (Carter et al., 2019; Mwangi et al., 2021) that co-production is a most effective approach to the design and operation of the FldEWS and the associated preparedness actions is most effective. The involvement of a wide range of stakeholders ensures that forecast information is decision-relevant and actionable and is necessary in developing Impact based Forecasting (IBF) to conform to WMO guidelines (WMO, 2015). Co-production requires considerable commitment and indeed resources to establish and maintain the necessary strong relationships (Carter et al., 2019). The SHEAR programme has developed an online training course in co-production specifically for climate services in Africa (https://walker.ac.uk/academy/learning-to-co-produce/).

More broadly, there should be greater cross-project and cross-agency partnerships and collaboration. This is essential for many reasons such as improving information collection and sharing, ensuring effective synergies between FldEWS and, for example, disaster risk reduction planning and long-term climate resilience and ensuring effective communication and communication of flood warnings.

Synergies between activities that fall under climate change adaptation and near-term disaster risk management should be enhanced. Strengthening capacity to deal with current high-impact weather and climate variability builds resilience to the increasing extremes of future climate change (Evans et al., 2020). There are some immediately obvious examples: (i) Baseline risk assessment and mapping are a pre-requisite for flood risk management (ii) FldEWS are already a priority activity under national adaptation planning. The scope to support those through adaptation finance should be explored as a priority.

All these priority recommendations presented here are consistent with what is required for effective Impact Based Forecasting for flood risk. Such systems are now being operationalised in various parts of the world (see Met Office, 2022 for examples) and the mandated agencies in Kenya can draw appropriate lessons and good practices. In our view, such developments demand a step change in existing modes of operation and in the capacities of the mandated agencies. This requires investment in all the relevant components of FldEWS including dedicated funds for contingency planning and preparedness action. Such investment may seem daunting but is very likely to be cost-effective in the long run and EWSs in general show a high return on investment (Global Commission on Adaptation, 2019). The opportunity afforded by international climate finance streams should be explored as an avenue to support such advances in FldEWS. Such investments in institutional capacities must be sustainable in the longer term (Dupar et al., 2021) and this kind of funding is best entrenched in government systems. We also note the lack of effective monitoring and evaluation of the value and benefits of EWS in Kenya. Collection and sharing of relevant data and robust systems for determining benefits should be implemented as part of continued investments.

Finally, there remains evidence of fragmentation in risk management policies and practices (exemplified through the need for national and county-specific EAPs see Sections 2.4 and 3.3). This issue should be addressed so that there is greater coherence in risk governance. The StERC project has supported the county government to draft and enact laws and policies that govern and create structures and funding streams for disaster management including floods. This should be scaled up to other counties. Furthermore, the same laws and policies are also needed at the national level to guide disaster preparedness and coordination amongst agencies. We propose that institutional and governance arrangements need to be streamlined including establishing a national flood management coordinating body that can work with NFMIAC in centralising flood risk data and facilitate preparedness funds that can be triggered by forecasts. It may be that a single disaster risk management authority that coordinates both flood and drought risk management may be the most effective structure.

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DATA AVAILABILITY STATEMENT

Data where appropriate is available upon request. However, Tana and Nzoia river flow data is held by Water Resources Authority and are not publicly available. GloFAS reforecast data is available online upon user account creation on https://cds.climate.copernicus.eu/#!/home.

ORCID

Augustine Kiptum https://orcid.org/0000-0003-3117-9368
Martin C. Todd https://orcid.org/0000-0003-4847-5921

REFERENCES

Abdrabo, M., Ama, E., Lennard, C., & Adelekan, I. O. (2014). Chapter 22 Africa. In: *Contribution of Working Group II to the Fifth Assessment Report of the Climate change 2014*: *Impacts*, *adaptation*, *and vulnerability*. *Part B*: *Regional aspects*, *January*.

Alfieri, L., Burek, P., Dutra, E., Krzeminski, B., Muraro, D., Thielen, J., & Pappenberger, F. (2013). GloFAS-global ensemble streamflow forecasting and flood early warning. *Hydrology and Earth System Sciences*, *17*(3), 1161–1175. https://doi.org/10.5194/HESS-17-1161-2013

Alfieri, L., European Commission, Burek, P. A., & Dutra, E. (2012). GloFAS—Global ensemble streamflow forecasting and flood early warning GloFAS—Global ensemble streamflow forecasting and flood early warning. *July 2014*. https://doi.org/10.5194/hess-17-1161-2013

Alfieri, L., Lorini, V., Hirpa, F. A., Harrigan, S., Zsoter, E., Prudhomme, C., & Salamon, P. (2020). A global streamflow reanalysis for 1980–2018. *Journal of Hydrology X*, *6*, 100049. https://doi.org/10.1016/J.HYDROA.2019.100049

Baker, J. L. (2012). Climate change, disaster risk, and the urban poor: Cities building resilience for a changing world. *Climate Change, Disaster Risk, and the Urban Poor*. https://doi.org/10.1596/978-0-8213-8845-7

Bazo, J., Singh, R., Destrooper, M., & de Perez, E. C. (2019). Pilot experiences in using seamless forecasts for early action: The "ready-set-go!" approach in the red cross. In A. W. Robertson & F. Vitart (Eds.), *Sub-Seasonal to Seasonal Prediction: The Gap between Weather and Climate Forecasting* (pp. 387–398). Elsevier. https://doi.org/10.1016/B978-0-12-811714-9.00018-8

Berhane, F., Zaitchik, B., & Dezfuli, A. (2014). Subseasonal analysis of precipitation variability in the Blue Nile River basin. *Journal of Climate*, *27*(1), 325–344. https://doi.org/10.1175/JCLI-D-13-00094.1

Bischiniotis, K., van den Hurk, B., Zsoter, E., Coughlan de Perez, E., Grillakis, M., & Aerts, J. C. J. H. (2019). Evaluation of a global ensemble flood prediction system in Peru. *Hydrological Sciences Journal*, *64*(10), 1171–1189. https://doi.org/10.1080/02626667.2019.1617868

Black, E. (2005). The relationship between Indian Ocean sea surface temperature and east African rainfall. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and*

Engineering Sciences, *363*(1826), 43–47. https://doi.org/10.1098/RSTA.2004.1474

Cafaro, C., Woodhams, B. J., Stein, T. H. M., Birch, C. E., Webster, S., Bain, C. L., Hartley, A., Clarke, S., Ferrett, S., & Hill, P. (2021). Do convection-permitting ensembles lead to more skillful short-range probabilistic rainfall forecasts over tropical east africa? *Weather and Forecasting*, *36*(2), 697–716. https://doi.org/10.1175/WAF-D-20-0172.1

Carter, S., Steynor, A., Vincent, K., Visman, E., & Waagsaether, K. (2019). *A manual for co-production in African weather and climate services: Home*. WISER.

CRED. (2022). *Centre for Research on the Epidemiology of Disasters Emergency Database*. CRED.

Dankers, R., Arnell, N. W., Clark, D. B., Falloon, P. D., Fekete, B. M., Gosling, S. N., Heinke, J., Kim, H., Masaki, Y., Satoh, Y., Stacke, T., Wada, Y., & Wisser, D. (2014). First look at changes in flood hazard in the inter-sectoral impact model Intercomparison project ensemble. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(9), 3257–3261. https://doi.org/10.1073/PNAS.1302078110

de Perez, E. C., Van Den Hurk, B., Van Aalst, M. K., Amuron, I., Bamanya, D., Hauser, T., Jongma, B., Lopez, A., Mason, S., De Suarez, J. M., Pappenberger, F., Rueth, A., Stephens, E., Suarez, P., Wagemaker, J., & Zsoter, E. (2016). Action-based flood forecasting for triggering humanitarian action. *Hydrology and Earth System Sciences*, *20*(9), 3549–3560. https://doi.org/10.5194/HESS-20-3549-2016

Development Initiatives. (2017). *Assessment of Kenya's preparedness to disasters caused by natural hazards: Floods, drought and disease outbreak*. Development Initiatives Retrieved from https://devinit.org/resources/assessment-of-kenyas-preparedness-to-disasters-caused-by-natural-hazards-floods-drought-and-disease-outbreak/#:~:text=Downloadthefullreporthere

Di Baldassarre, G., Montanari, A., Lins, H., Koutsoyiannis, D., Brandimarte, L., & Blschl, G. (2010). Flood fatalities in Africa: From diagnosis to mitigation. *Geophysical Research Letters*, *37*(22), 22402. https://doi.org/10.1029/2010GL045467

Di Baldassarre, G., Nardi, F., Annis, A., Odongo, V., Rusca, M., & Grimaldi, S. (2020). Brief communication: Comparing hydrological and hydrogeomorphic paradigms for global flood hazard mapping. *Natural Hazards and Earth System Sciences*, *20*(5), 1415–1419. https://doi.org/10.5194/NHESS-20-1415-2020

Döll, P., Trautmann, T., Gerten, D., Schmied, H. M., Ostberg, S., Saaed, F., & Schleussner, C. F. (2018). Risks for the global freshwater system at 1.5 °C and 2 °C global warming. *Environmental Research Letters*, *13*(4), 044038. https://doi.org/10.1088/1748-9326/AAB792

Dupar, M., Weingärtner, L., & Opitz-stapleton, S. (2021). *How to develop sustainable climate services a road map for public investors and project managers*. WISER.

ESA. (2022). *Sentinel-2—Missions—Sentinel Online*. ESA Retrieved from https://sentinel.esa.int/web/sentinel/missions/sentinel-2

Evans, B. E., Rowell, D. P., & Semazzi, F. H. M. (2020). The future-climate, current-policy framework: Towards an approach linking climate science to sector policy development. *Environmental Research Letters*, *15*(11). https://doi.org/10.1088/1748-9326/abbeb9

FloodList. (2020). *Kenya—More than 100 dead as floods and landslides continue*. FloodList Retrieved from https://floodlist.com/africa/kenya-floods-update-may-2020

Fourth, T. (2011). *How climate change is driving extreme weather in the developing world—Kenyan case study*. Trócaire.

Funk, C., Hoell, A., Nicholson, S., Korecha, D., Galu, G., Artan, G., Teshome, F., Hailermariam, K., Segele, Z., Harrison, L., Tadege, A., Atheru, Z., Pomposi, C., & Pedreros, D. (2019). Examining the potential contributions of extreme "western v" sea surface temperatures to the 2017 March–June east African drought. *Bulletin of the American Meteorological Society*, *100*(1), S55–S60. https://doi.org/10.1175/BAMS-D-18-0108.1

Gebremedhin, E. T., Basco-Carrera, L., Jonoski, A., Iliffe, M., & Winsemius, H. (2020). Crowdsourcing and interactive modelling for urban flood management. *Journal of Flood Risk Management*, *13*(2), e12602. https://doi.org/10.1111/JFR3.12602

Global Commission on Adaptation. (2019). Adapt now: A global call for leadership on climate resilience—Global center on adaptation. Retrieved from https://gca.org/reports/adapt-now-a-global-call-for-leadership-on-climate-resilience/

GoK. (2016). *Kenya National Adaptation Plan 2015–2030 enhanced climate resilience towards the attainment of vision 2030 and beyond*. GoK.

GoK. (2018). National climate change action plan (Kenya): 2018-2022. In *Volume 3: Mitigation technical analysis report* (p. 3). Ministry of Environment and Forestry.

GoK. (2019). *Water resources authority strategic plan*. GoK.

Groeve, T., Vernaccini, L., & Poljansek, K. (2014). *Index for risk management—INFORM. Concept and methodology version 2016. EUR 27521, JRC Science for Policy Reports—European Commission [JRC98090]*. Publications Office of the European Union. https://doi.org/10.2788/636388

Gumbel, E. J. (1958). Statistics of extremes. *Journal of the Royal Statistical Society. Series A (General)*, *122*(2), 243. https://doi.org/10.2307/2342609

Haile, G. G., Tang, Q., Hosseini-Moghari, S. M., Liu, X., Gebremicael, T. G., Leng, G., Kebede, A., Xu, X., & Yun, X. (2020). Projected impacts of climate change on drought patterns over East Africa. *Earth's Futures*, *8*(7), e2020EF001502. https://doi.org/10.1029/2020EF001502

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H., & Kanae, S. (2013). Global flood risk under climate change. *Nature Climate Change*, *3*(9), 816–821. https://doi.org/10.1038/nclimate1911

Hirons, L., Thompson, E., Dione, C., Indasi, V. S., Kilavi, M., Nkiaka, E., Talib, J., Visman, E., Adefisan, E. A., de Andrade, F., Ashong, J., Mwesigwa, J. B., Boult, V. L., Diédhiou, T., Konte, O., Gudoshava, M., Kiptum, C., Amoah, R. K., Lamptey, B., … Woolnough, S. (2021). Using co-production to improve the appropriate use of sub-seasonal forecasts in Africa. *Climate Services*, *23*, 100246. https://doi.org/10.1016/J.CLISER.2021.100246

Hirpa, F. A., Salamon, P., Beck, H. E., Lorini, V., Alfieri, L., Zsoter, E., & Dadson, S. J. (2018). Calibration of the global flood awareness system (GloFAS) using daily streamflow data. *Journal of Hydrology*, *566*, 595–606. https://doi.org/10.1016/J.JHYDROL.2018.09.052

IFRC. (2022). *Early warning, early action, IFRC: Community early warning systems*. IFRC Retrieved from https://www.ifrc.org/early-warning-early-action

Indeje, M., Semazzi, F. H. M., & Ogallo, L. J. (2000). ENSO signals in east African rainfall seasons. *International Journal of*

Climatology, *20*(1), 19–46. https://doi.org/10.1002/(SICI)1097-0088(200001)20:1<19::AID-JOC449>3.0.CO;2-0

KDI. (2022). *3Di hydrodynamic simulation software. 3Di water Managemen*. KDI Retrieved from https://kounkuey.org/projects/

Kolstad, E. W., MacLeod, D., & Demissie, T. D. (2021). Drivers of subseasonal forecast errors of the east African short rains. *Geophysical Research Letters*, *48*(14), e2021GL093292. https://doi.org/10.1029/2021GL093292

Lumbroso, D. (2018). How can policy makers in sub-Saharan Africa make early warning systems more effective? The case of Uganda. *International Journal of Disaster Risk Reduction*, *27*, 530–540. https://doi.org/10.1016/J.IJDRR.2017.11.017

Lumbroso, D. (2020). Flood risk management in Africa. *Journal of Flood Risk Management*, *13*(3), e12612. https://doi.org/10.1111/JFR3.12612

Lumbroso, D., Brown, E., & Ranger, N. (2016). Stakeholders' perceptions of the overall effectiveness of early warning systems and risk assessments for weather-related hazards in Africa, the Caribbean and South Asia. *Natural Hazards*, *84*(3), 2121–2144. https://doi.org/10.1007/S11069-016-2537-0

MacLeod, D. (2019). Seasonal forecasts of the east African long rains: Insight from atmospheric relaxation experiments. *Climate Dynamics*, *53*(7–8), 4505–4520. https://doi.org/10.1007/S00382-019-04800-6/FIGURES/10

Macleod, D., Kilavi, M., Mwangi, E., Ambani, M., Osunga, M., Robbins, J., Graham, R., Rowhani, P., & Todd, M. C. (2021). Are Kenya meteorological department heavy rainfall advisories useful for forecast-based early action and early preparedness for flooding? *Natural Hazards and Earth System Sciences*, *21*(1), 261–277. https://doi.org/10.5194/nhess-21-261-2021

Macleod, D. A., Dankers, R., Graham, R., Guigma, K., Jenkins, L., Todd, M. C., Kiptum, A., Kilavi, M., Njogu, A., & Mwangi, E. (2021). Drivers and subseasonal predictability of heavy rainfall in equatorial East Africa and relationship with flood risk. *Journal of Hydrometeorology*, *22*(4), 887–903. https://doi.org/10.1175/JHM-D-20-0211.1

Malamud, B. D., Mwangi, E., Gill, J., Hussain, E., Taylor, F., Sakic Trogrlic, R., Malamud, B. D., Mwangi, E., Gill, J., Hussain, E., Taylor, F., & Sakic Trogrlic, R. (2021). *Multiple-hazards and their interactions in urban low-to-middle income countries: A case study from Nairobi [EGU21-16053]*. EGUGA. https://doi.org/10.5194/EGUSPHERE-EGU21-16053

Marsham, J. (2020). *East Africa faces triple crisis of Covid-19, locusts and floods*. Climate Home News Retrieved from https://www.climatechangenews.com/2020/05/11/east-africa-faces-triple-crisis-covid-19-locusts-floods/

Masson-Delmotte, V., & Zhai, P. (2021). Climate change 2021 the physical science basis summary for policymakers working group I contribution to the sixth assessment report of the intergovernmental panel on climate change. In *Climate change 2021: The physical science basis. IPCC*.

Met Office. (2022). *Accelerating impact-based forecasting*. Met Office Retrieved from https://www.metoffice.gov.uk/research/approach/collaboration/newton/insights/accelerating-impact-based-forecasting

Muita, R., Dougill, A., Mutemi, J., Aura, S., Graham, R., Awolala, D., Nkiaka, E., Hirons, L., & Opijah, F. (2021). Understanding the role of user needs and perceptions related to subseasonal and seasonal forecasts on Farmers' decisions in Kenya: A systematic review. *Frontiers in Climate*, *3*, 10. https://doi.org/10.3389/FCLIM.2021.580556/BIBTEX

Mulligan, J., Harper, J., Kipkemboi, P., Ngobi, B., & Collins, A. (2017). Community-responsive adaptation to flooding in Kibera, Kenya. *Proceedings of the Institution of Civil Engineers: Engineering Sustainability*, *170*(5), 268–280. https://doi.org/10.1680/JENSU.15.00060/ASSET/IMAGES/SMALL/JENSU170-0268-F9.GIF

Mwangi, E., Taylor, O., Todd, M. C., Visman, E., Kniveton, D., Kilavi, M., Ndegwa, W., Otieno, G., Waruru, S., Mwangi, J., Ambani, M., Abdillahi, H., MacLeod, D., Rowhani, P., Graham, R., & Colman, A. (2021). Mainstreaming forecast based action into national disaster risk management systems: Experience from drought risk management in Kenya. *Climate and Development*, *14*, 741–756. https://doi.org/10.1080/17565529.2021.1984194

Neal, J., Schumann, G., & Bates, P. (2012). A subgrid channel model for simulating river hydraulics and floodplain inundation over large and data sparse areas. *Water Resources Research*, *48*(11), 11506. https://doi.org/10.1029/2012WR012514

Norman, H. (2018). Bridge the gap [since 1997, 2019–2021]. *Meteorological Technology International*, *2021*, 8–12 Retrieved from https://www.meteorologicaltechnologyinternational.com/online-magazines/in-this-issue-april-2021.html

Onencan, A., Kortmann, R., Kulei, F., & Enserin, B. (2016). MAFURIKO: Design of Nzoia basin location based flood game. *Procedia Engineering*, *159*, 133–140. https://doi.org/10.1016/J.PROENG.2016.08.138

Otieno, O. M., Abdillahi, H. S., Wambui, E. M., & Kiprono, K. S. (2019). Flood impact-based forecasting for early warning and early action in tana River Basin, Kenya. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS archives*, *42*(3/W8), 293–300. https://doi.org/10.5194/isprs-archives-XLII-3-W8-293-2019

Pappenberger, F., Dutra, E., Wetterhall, F., & Cloke, H. L. (2012). Deriving global flood hazard maps of fluvial floods through a physical model cascade. *Hydrology and Earth System Sciences*, *16*(11), 4143–4156. https://doi.org/10.5194/HESS-16-4143-2012

Parker, D. J., Blyth, A. M., Woolnough, S. J., Dougill, A. J., Bain, C. L., de Coning, E., Diop-Kane, M., Foamouhoue, A. K., Lamptey, B., Ndiaye, O., Ruti, P., Adefisan, E. A., Amekudzi, L. K., Antwi-Agyei, P., Birch, C. E., Cafaro, C., Carr, H., Chanzu, B., Clarke, S. J., … Youds, L. (2022). The African SWIFT project: Growing science capability to bring about a revolution in weather prediction. *Bulletin of the American Meteorological Society*, *103*(2), E349–E369. https://doi.org/10.1175/BAMS-D-20-0047.1

Passerotti, G., Massazza, G., Pezzoli, A., Bigi, V., Zsótér, E., & Rosso, M. (2020). Hydrological model application in the Sirba River: Early warning system and GloFAS improvements. *Water*, *12*(3), 620. https://doi.org/10.3390/W12030620

Quagliolo, C., Comino, E., & Pezzoli, A. (2021). Experimental flash floods assessment through urban flood risk mitigation (UFRM) model: The case study of Ligurian coastal cities. *Frontiers in Water*, *3*, 50. https://doi.org/10.3389/FRWA.2021.663378/BIBTEX

Roberts, A. J., Fletcher, J. K., Groves, J., Marsham, J. H., Parker, D. J., Blyth, A. M., Adefisan, E. A., Ajayi, V. O., Barrette, R., de Coning, E., Dione, C., Diop, A., Foamouhoue, A. K., Gijben, M., Hill, P. G., Lawal, K. A., Mutemi, J., Padi, M., Popoola, T. I., … Woodhams, B. J. (2021). Nowcasting for Africa: Advances, potential and value. *Weather*, *77*, 250–256. https://doi.org/10.1002/WEA.3936

Roberts, R. D., Goodman, S. J., Wilson, J. W., Watkiss, P., Powell, R., Petersen, R. A., Bain, C., Faragher, J., Chang'a, L. B., Kapkwomu, J. K., Oloo, P. N., Sebaziga, J. N., Hartley, A., Donovan, T., Mittermaier, M., Cronce, L., & Virts, K. S. (2022). Taking the HIGHWAY to save lives on Lake Victoria. *Bulletin of the American Meteorological Society*, *103*(2), E485–E510. https://doi.org/10.1175/BAMS-D-20-0290.1

Rode Kruis Dashboards. (2022). Retrieved from https://dashboard.510.global/#!/.

Rowell, D. P., Booth, B. B. B., Nicholson, S. E., & Good, P. (2015). Reconciling past and future rainfall trends over East Africa. *Journal of Climate*, *28*(24), 9768–9788. https://doi.org/10.1175/JCLI-D-15-0140.1

Sampson, C. C., Smith, A. M., Bates, P. B., Neal, J. C., Alfieri, L., & Freer, J. E. (2015). A high-resolution global flood hazard model. *Water Resources Research*, *51*(9), 7358–7381. https://doi.org/10.1002/2015WR016954

Sen, S. M. H. (2020). *DARAJA study: Co-designing weather and climate information services*. Resurgence Retrieved from https://www.resurgence.io/news/daraja-co-designing-weather-and-climate-information-services/

Shilenje, Z. W., & Ogwang, B. A. (2015). The role of Kenya meteorological Service in Weather Early Warning in Kenya. *International Journal of Atmospheric Sciences*, *2015*, 1–8. https://doi.org/10.1155/2015/302076

Smith, A., Sampson, C., & Bates, P. (2015). Regional flood frequency analysis at the global scale. *Water Resources Research*, *51*(1), 539–553. https://doi.org/10.1002/2014WR015814

Speight, L. J., Cranston, M. D., White, C. J., & Kelly, L. (2021). Operational and emerging capabilities for surface water flood forecasting. *Wiley Interdisciplinary Reviews Water*, *8*(3), e1517. https://doi.org/10.1002/WAT2.1517

Stephens, E., Day, J. J., Pappenberger, F., & Cloke, H. (2015). Precipitation and floodiness. *Geophysical Research Letters*, *42*(23), 10316–10323. https://doi.org/10.1002/2015GL066779

Thielen, J., Alfieri, L., Burek, P., Kalas, M., Salamon, P., Thiemig, V., de Roo, A., Muraro, D., Pappenberger, F., & Dutra, E. (2012). The global flood awareness system (GloFAS). *Comprehensive Flood Risk Management*. https://doi.org/10.1201/B13715-225

UNICEF. (2018). *Kenya floods response update—8 June 2018, flash update*. ReliefWeb Retrieved from https://reliefweb.int/report/kenya/kenya-floods-response-update-8-june-2018-flash-update

UNISDR. (2015a). *Disaster risk reduction In Africa: Status report executive summary* (Vol. 5). UNISDR.

UNISDR. (2015b). *Disaster risk reduction in Africa*. UNISDR Retrieved from https://www.undrr.org/publication/unisdr-annual-report-2015

van der Knijff, J. M., Younis, J., & de Roo, A. P. J. (2008). LISFLOOD: A GIS-based distributed model for river basin scale water balance and flood simulation. *International Journal of Geographical Information Science*, *24*(2), 189–212. https://doi.org/10.1080/13658810802549154

Vitart, F. (2017). Madden—Julian oscillation prediction and teleconnections in the S2S database. *Quarterly Journal of the Royal Meteorological Society*, *143*(706), 2210–2220. https://doi.org/10.1002/QJ.3079

Vogel, P., Knippertz, P., Fink, A. H., Schlueter, A., & Gneiting, T. (2018). Skill of global raw and postprocessed ensemble predictions of rainfall over northern tropical Africa. *Weather and Forecasting*, *33*(2), 369–388. https://doi.org/10.1175/WAF-D-17-0127.1

Vogel, P., Knippertz, P., Fink, A. H., Schlueter, A., & Gneiting, T. (2020). Skill of global raw and postprocessed ensemble predictions of rainfall in the tropics. *Weather and Forecasting*, *35*(6), 2367–2385. https://doi.org/10.1175/WAF-D-20-0082.1

Weingärtner, L., Jaime, C., Todd, M., Levine, S., Mcdowell, S., & Macleod, D. (2019). *Reducing flood impacts through forecast-based action entry points for social protection systems in Kenya*. Overseas Development Institute.

WISER. (2020). *Co-production: Effective approaches for service development*. Met Office Retrieved from https://www.metoffice.gov.uk/about-us/what/working-with-other-organisations/international/projects/wiser/co-production

WMO. (2015). *WMO guidelines on multi-hazard impact-based forecast and warning services (WMO)*. WMO.

WMO. (2020). *State of climate services 2020 report: Move from early warnings to early action*. World Meteorological Organization Retrieved from https://public.wmo.int/en/media/press-release/state-of-climate-services-2020-report-move-from-early-warnings-early-action

WMO-S2S. (2022). *Improved support in decision making over eastern Africa through the use of real time S2S datasets (RegionActv. Improved support in decision making over eastern Africa through utilizing of real time S2S datasets)—XWiki*. World Meteorological Organization Retrieved from http://www.s2sprediction.net/xwiki/bin/view/RegionActv/Improved+support+in+decision+making+over+Eastern+Africa+through+utilizing+of+real+time+S2S+datasets

World Bank. (2021). *Climate risk country profile: Kenya*. World Bank.

Yamazaki, D., Ikeshima, D., Sosa, J., Bates, P. D., Allen, G. H., & Pavelsky, T. M. (2019). MERIT hydro: A high-resolution global hydrography map based on latest topography dataset. *Water Resources Research*, *55*(6), 5053–5073. https://doi.org/10.1029/2019WR024873

Yamazaki, D., Ikeshima, D., Tawatari, R., Yamaguchi, T., O'Loughlin, F., Neal, J. C., Sampson, C. C., Kanae, S., & Bates, P. D. (2017). A high-accuracy map of global terrain elevations. *Geophysical Research Letters*, *44*(11), 5844–5853. https://doi.org/10.1002/2017GL072874

Zsoter, E., Prudhomme, C., Stephens, E., Pappenberger, F., & Cloke, H. (2020). Using ensemble reforecasts to generate flood thresholds for improved global flood forecasting. *Journal of Flood Risk Management*, *13*(4), e12658. https://doi.org/10.1111/JFR3.12658

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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