Flood Early Warning Systems: A Review Of Benefits, Challenges And Prospects

Duminda Perera, Ousmane Seidou, Jetal Agnihotri, Mohamed Rasmy, Vladimir Smakhtin, Paulin Coulibaly, Hamid Mehmood

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CONTENTS

EXECUTIVE SUMMARY

Floods are major water-related disasters that affect millions of people resulting in thousands of mortalities and billion-dollar losses globally every year. Flood Early Warning Systems (FEWS) - one of the floods risk management measures - are currently operational in many countries. The UN Office for Disaster Risk Reduction recognises their importance and strongly advocates for an increase in their availability under the targets of the Sendai Framework for Disaster Risk Reduction, and Sustainable Development Goals (SDGs). However, despite widespread recognition of the importance of FEWS for disaster risk reduction (DRR), there's a lack of information on their availability and status around the world, their benefits and costs, challenges and trends associated with their development.

This report contributes to bridging these gaps by analyzing the responses to a comprehensive online survey with over 80 questions on various components of FEWS (risk knowledge, monitoring and forecasting, warning dissemination and communication, and response capabilities), investments into FEWS, their operational effectiveness, benefits, and challenges. FEWS were classified as technologically "basic", "intermediate" and "advanced" depending on the existence and sophistication of FEWS` components such as hydrological data collection systems, data transfer systems, flood forecasting methods, and early warning communication methods. The survey questionnaire was distributed to flood forecasting and warning centers around the globe; the primary focus was developing and least-developed countries (LDCs). The questionnaire is available here: https://inweh.unu.edu/questionnaire-evaluation-of-flood-early-warning-systems/ and can be useful in its own right for similar studies at national or regional scales, in its current form or with case-specific modifications.

Survey responses were received from 47 developing (including LDCs) and six developed countries. Additional information for some countries was extracted from available literature. Analysis of these data suggests the existence of an equal number of "intermediate" and "advanced" FEWS in surveyed river basins. While developing countries overall appear to progress well in FEWS implementation, LDCs are still lagging behind since most of them have "basic" FEWS. The difference between types of operational systems in developing and developed countries appear to be insignificant; presence of basic, intermediate or advanced FEWS depends on available investments for system developments and continuous financing for their operations, and there is evidence of more financial support — on the order of USD 100 million — to FEWS in developing countries thanks to international aid. However, training the staff and maintaining the FEWS for long-term operations are challenging.

About 75% of responses indicate that river basins have inadequate hydrological network coverage and back-up equipment. Almost half of the responders indicated that their models are not advanced and accurate enough to produce reliable forecasts. Lack of technical expertise and limited skilled manpower to perform forecasts was cited by 50% of respondents. The primary reason for establishing FEWS, based on the survey, is to avoid property damage; minimizing causalities and agricultural losses appear to be secondary reasons. The range of the community benefited by FEWS varies, but 55% of FEWS operate in the range between 100,000 to 1 million of population.

The number of flood disasters and their causalities has declined since the year 2000, while 50% of currently operating FEWS were established over the same period. This decline may be attributed to the combined DRR efforts, of which FEWS are an integral part.

In lower-middle-income and low-income countries, economic losses due to flood disasters may be smaller in absolute terms, but they represent a higher percentage of such countries' GDP. In high-income countries, higher flood-related losses accounted for a small percentage of their GDP.

To improve global knowledge on FEWS status and implementation in the context of Sendai Framework and SDGs, the report's recommendations include: i) coordinate global investments in FEWS development and standardise investment reporting; ii) establish an international hub to monitor the status of FEWS in collaboration with the national responsible agencies. This will support the sharing of FEWS-related information for accelerated global progress in DRR; iii) develop a comprehensive, index-based ranking system for FEWS according to their effectiveness in flood disaster mitigation. This will provide clear standards and a roadmap for improving FEWS' effectiveness, and iv) improve coordination between institutions responsible for flood forecasting and those responsible for communicating warnings and community preparedness and awareness.

Keywords: *Flood early warning systems (FEWS); flood forecasting center (FFC); disaster risk reduction (DRR); flood disasters; benefits; investments; Sendai framework; sustainable development goals (SDGs)*

INTRODUCTION

Water-Related Disasters (WRD) account for an overwhelming 90% of all natural disasters globally (Centre for Research on Epidemiology of Disasters Emergency Events Database – CRED's EM-DAT — is used in this report to provide global, continental, national or regional disaster statistics, https://www.emdat.be/). Since the year 2000 through to the end of 2018, a total of 5,338 WRD have been reported and led to over 326,000 fatalities and economic losses of more than USD 1.7 trillion globally. Floods accounted for about 54 % of all WRDs. Asia appears to be the hardest-hit continent, with 41% of all flood disaster events, followed by Africa (23%), the Americas (21%), Europe (13%) and Oceania (3%). Of the deaths caused by all WRDs from 2001 to 2018, some 93,470 were due to floods. During the same period, floods alone were responsible for economic losses of nearly USD 500 billion globally – about one-third of the total financial losses caused by all WRD. Asia was the most vulnerable with 71% of the total fatalities and 63% of the overall economic damages recorded since 2001. In 2018 alone, 50 flood disasters were reported in Asia, causing nearly 2,000 casualties and losses of USD 16 billion. China, India, and Indonesia were Asia's hardest-hit nations, with over 100 flood disaster events since year 2000. Although there is some evidence of a gradual decline in frequency of flood disasters and associated mortalities after 2000, compared to the 20th century (1901-2000), the economic damages have been continually increasing (EM-DAT 2018).

Various structural and non-structural flood mitigation measures are implemented with the aim of minimizing flood disasters and they have cost some several billion dollars globally (Faisal et al., 1999). Examples of structural measures include levees, reservoirs, diversion channels, and spillways, while non-structural measures include FEWS, land-use planning and zoning, rainwater harvesting, flood insurance schemes, and awareness campaigns. Both types of measures can reduce casualties and economic losses, and therefore are critical for international DRR efforts. Global focus on DRR has significantly increased since 2000 when the Millennium Declaration called on global community to "*intensify our collective efforts to reduce the number and effects of natural and man-made disasters*" (United Nations, 2000). The Hyogo Framework for Action was initiated by the United Nations in 2005 to reduce the disaster-related impacts before 2015 (UNDRR, 2005). In 2015, as a successor to Hyogo Framework for Action, the Sendai Framework for Disaster Risk Reduction (further referred to as "Sendai Framework") was adopted with seven targets and four priorities for action (UNDRR, 2015). Also, in 2015, world leaders adopted 17 Sustainable Development Goals (SDGs), which included 169 specific targets. There are some 25 targets related to DRR in 10 of the 17 SDGs. Among these, targets 11.5 and 11.b are aimed at reducing number of deaths, people affected, and economic losses caused by disasters — specifically from WRD — by 2030, the end of the current SDG period; Target 13.1 aims to strengthen the integration between disaster and climate resilience to protect broader development paths, and Target 9.1 focuses on the development of disaster-resilient infrastructure.

FEWS form a major part of global DRR effort. UNDRR (2017) defines early warning system as "*an integrated system of hazard monitoring, forecasting and prediction, disaster risk assessment, communication and preparedness activities systems and processes that enable individuals, communities, governments, businesses and others to take timely actions to reduce disaster risks in advance of hazardous events*". WMO (2011) defines flood forecasting and warning systems as "*linkage between the basic structures*" that "*include provision of specific forecasts with magnitude and timing of rainfall, establishment of a network of hydrometric stations, operation of real-time flood forecasting model software and issuance of early flood warnings*".

This report follows a more encompassing UNDRR terminology for early warning systems, according to which an effective end-to-end FEWS must include four key elements: (1) risk knowledge, (2) monitoring and forecasting, (3) warning dissemination and communication, and (4) response capabilities (UNDRR, 2006). FEWS directly address Sendai Framework target 7 that focuses on "*substantially increasing the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to people*". FEWS are also critical in the context of other six targets of the Sendai framework.

The ability of FEWS to reduce flood risks is widely acknowledged (UNDRR, 2004; WMO, 2013; Pappenberger et al., 2015; Thielen-del Pozo et al., 2015). However, a global picture of how well they function on the ground, especially in the developing world, is lacking. The Operational effectiveness of FEWS is mostly unknown and the barriers they face are not spelled out. It is also not clear how much they contribute to SDGs and Sendai Framework targets in terms of minimizing flood-related impacts. This report aims to at least raise and, to an extent possible for a short publication, initially address these gaps by:

- Performing a comprehensive analysis of the current state of operational FEWS globally
- Evaluating operational effectiveness of FEWS measured by comparison of investments that went into these systems' development, and various benefits obtained due to their implementation
- Identifying the challenges that remain in the components of FEWS and which pose as barriers to achievement of global objectives by the end of SDG period

The target audience for this report includes flood forecasting and management professionals who may be looking for synthesis of such information to better understand the current state of FEWS around the globe and its contribution to DRR and SDGs; international donors, private foundations, and government organisations sponsoring FEWS to better shape their investment decisions; policymakers including ministerial personnel tasked with implementation of Sendai Framework; disaster risk managers concerned with the state of global efforts and existing gaps that remain to achieve SDGs; non-governmental organisations promoting DRR at regional, national, sub-continental or continental scale, and members of the general public who may be interested in FEWS development, and maintenance, FEWS benefits, and existing challenges.

CURRENT STATE OF OPERATIONAL FEWS ACROSS THE WORLD

The survey framework

A comprehensive questionnaire with 84 questions on the four FEWS' components, investments that went into FEWS, their direct and indirect benefits, operational effectiveness and technical, financial, social and political challenges was prepared. The whole questionnaire is too lengthy to include in this report, but its structural summary is given in Table 1, and its full version can be downloaded from inweh.unu.edu. An online survey software was used to distribute the questionnaire to institutions dealing with flood forecasting and early warnings in various countries across the world. The completed survey responses were received from 53 countries, including 47 developing and 6 developed. A detailed list of the countries that responded, the information on the river basins included, and institutions governing FEWS is provided in the Annex. An attempt was also made to identify from existing literature FEWS in the countries not represented in the online survey.

FEWS Categorisation

For the purposes of the survey and generalisation, FEWS are categorised here into three groups, as defined in Table 2. A "Technologically basic" system uses simple methods such as upstream water level observations to predict floods and does not involve a dedicated Flood Forecasting Centre (FFC) with technical professionals.

In "technologically intermediate" FEWS, limited technical resources are available for a systematic approach to predict floods. For instance, it does not include a flood forecasting system; instead, warning is issued based on past experiences of flood forecasting professionals and real-time observations.

Table 1: Structural summary of the FEWS questionnaire

Component	Major question types	Number of Questions
General	FEWS category of the target area, river basin details	2
Risk knowledge	Implementation of FEWS, residents, land-use, assets in target area, flood hazard maps	7
Monitoring	Gauges and its types, ways to monitor floods	5
Flood forecasting	Common flood types, hydrological model used, frequency of flood forecasts	6
Warning dissemination	End receivers, ways to disseminate warnings, frequency of warning updates	9
Response capabilities	Community's response, local support for children, women and elderly	3
Preparedness for evacuation	Programs for community awareness, step-wise evacuation procedure, self-protection measures	5
Investments	Sources of investment, amount of budget received, annual operating cost	9
Operational effectiveness	FEWS evaluation, accuracy of the system, financial cost of false alarm	7
Benefits	Lives saved, damages avoided, benefits to the target area, upgradation of the system	10
Gaps	Technical, social, political, financial challenges	21

Table 2: Categorisation of FEWS

Types of FEWS	Characteristics
Technologically basic	Manual data collection and transfer Qualitative forecast performed based on observations Community or local authority involved (None of following features are involved in this type of FEWS: Modern equipment, data collection, telemetric data communication, quantitative prediction, modeling)
Technologically intermidiate	Real-time data available from river and rainfall gauges No capacity for modeling-based flood forecasting Warnings issued based on data collected and past experiences
Technologically advanced	Telemetric data collection and transfer Modeling-based flood forecasting available Continuous monitoring and updates provided once the flood warning is issued

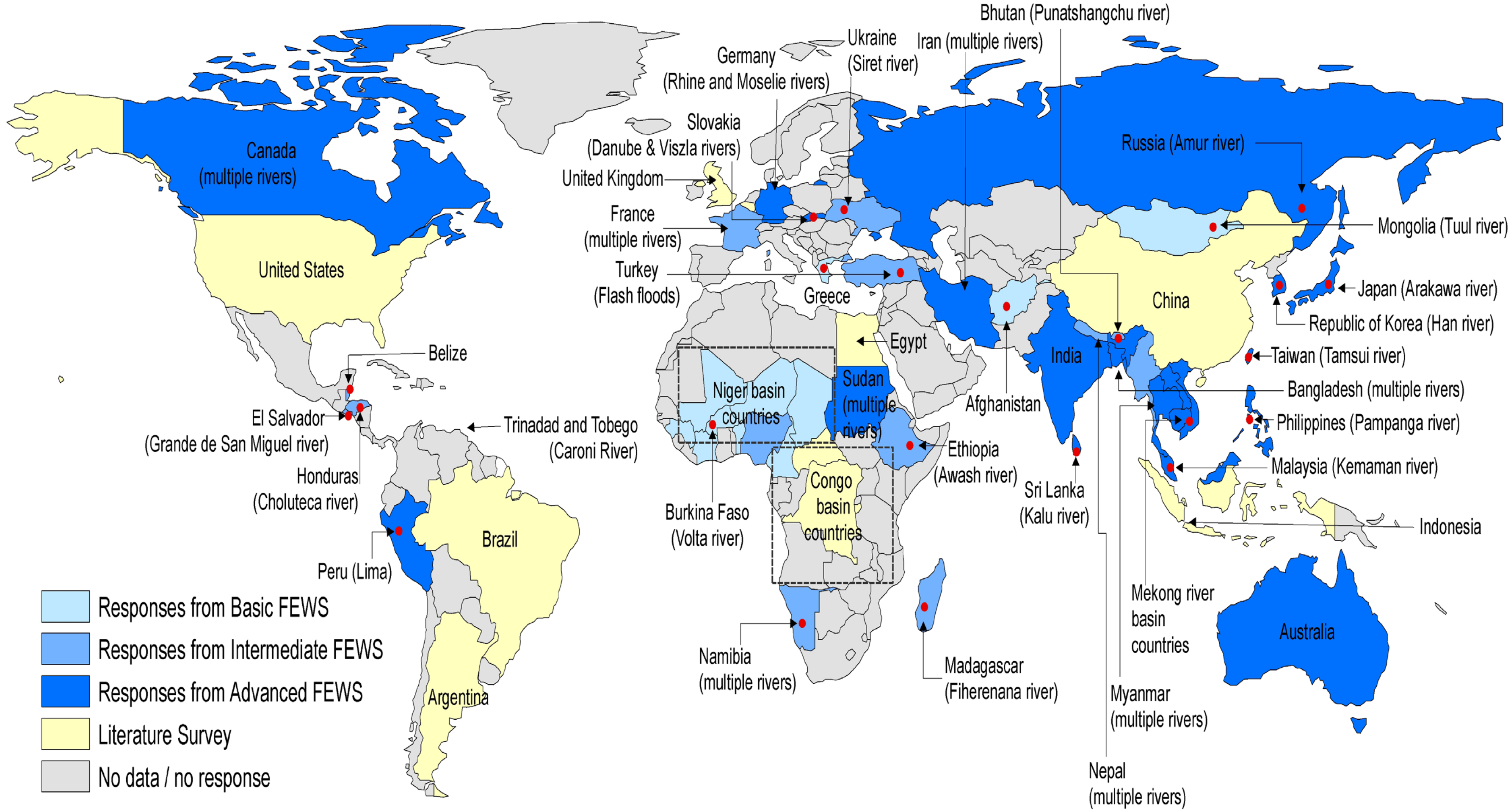


Figure 1: FEWS types identified through survey and literature. The map shows types of FEWS in countries responded to the survey or identified through literature. Three FEWS categories (explained in Table 2) are shown by different colours. - This does not reflect each and every FEWS in a country since different river basins may have different FEWS.

A "technologically advanced" FEWS involves sophisticated and systematic approach with sufficient technical resources including hydrologic and hydraulic model-based forecasting, telemetric observation systems. Based on this classification, Figure 1 maps the type of FEWS operational in each river basin for which survey responses were obtained. Respective percentages of Advanced, Intermediate and Basic FEWS – from responses - are 43%, 38% and 19%. According to the respondents, most river basins in Asia have advanced systems and only few basins are covered by basic or intermediate FEWS. Most African river basins appear to have basic systems. Surprisingly, no noticeable difference was found between the systems used by developing and developed countries. This may be because most systems in developing countries are a result of international cooperation projects and therefore their framework is often inherited from developed countries.

Additional literature review helped to identify 15 more countries where FEWS are in operation, although information extracted was not as comprehensive as that received from the online survey. In Australia, advanced FEWS are operated under the Australian Bureau of Meteorology covering all the state and territory governments. Financial aid for the implementation and improvements for flood warning services comes within the scope of support provided by the Australian Government to the States and Territories to enhance the resilience of communities against the impact of floods (BoM, 2018). Argentina recently developed an early flood detection and warning system with the technical aid from the private sector to minimise the flood disasters in the province of Buenos Aires (www.libelium.com). In Brazil, advanced flood forecasting is available in various locations including Doce River Basin, (83,400 km², Colatina city ~ 120,000 inhabitants), São Francisco River Basin (641,000 km²) and Tocantins River Basin (300,000 km²) mainly having two purposes (i) the scheduling of hydropower reservoirs operation; and (ii) flood forecasting in vulnerable locations to mitigate flood risk (Adams and Pagano, 2016). Cools et al (2016) emphasises the lessons from flood early warning giving three examples of operating FEWS in Belgium, Egypt and Mali. A FEWS was established following the flood catastrophe in the Demer River in 1998 in the Flanders region of Belgium. At present, it is an operational advanced system incorporating weather forecasting, radar, and a dense network of ground-based rainfall gauges and rainfall-runoff, and hydrodynamic model with the capacity of providing short-term (48 hours) and long-term (10 days) forecasts. Recently implemented basic FEWS in Egypt and Mali (in the floodplain of inner Niger Delta), operate under limited data and institutional capacity.

The Chinese government has invested more than 28 billion Yuan (~USD 4 billion) in mitigating flash floods over 2,058 counties and 30 provinces, including autonomous regions and municipalities (Liu et al., 2018). Among the flood risk mitigation efforts in China, establishment of FEWS is a primary activity, assembling state of the art monitoring, modeling and communication technologies. According to Liu et al. (2018), over 740,000 people of China living in areas prone to flash floods benefit from Chinese flood monitoring and early warning platform. The Congo River basin, which covers nine countries (Angola, Burundi, Central African Republic, Democratic Republic of Congo, Cameroon, Republic of Congo, Rwanda, Tanzania, and Zambia) hosts several FEWS, which are for the most part severely limited in resources such as hydrological stations, technology and human resources to produce accurate flood warnings. Thus, they function as basic level systems (Adams and Pagano, 2016). In the United Kingdom, the Environment Agency is the lead authority, which operates its FFC in Exeter. Flood warning service is provided to 20 warning areas that cover the whole country, as well as for all main watercourses and many coastal communities (Environment Agency, 2009). Semarang city in Indonesia's Central Java province suffered floods in 2012 due to the Bringin river overflow. The local government joined with international agencies and local stakeholders to develop a FEWS primarily to deal with flash floods. With advanced instruments and modeling, Semarang city now operates an advanced FEWS in collaboration with local communities to minimise flood impacts (Iglesias, 2015). FEWS mentioned above were among those identified in a literature review and not represented in this study`s questionnaire survey. For various reasons, access to operational information about other FEWS functioning in various parts of the world is very limited, as there is no established information hub summarizing various features of existing FEWS, nor common protocols on how to report them.

FEWS' Components

Risk Knowledge

Risk knowledge forms the foundation of early warning systems and includes vulnerability assessment through collection of quantitative information about the target area of the system, mainly regarding the reasons to implement FEWS, flood hazard maps availability, land-use of the downstream area, population and financial value of assets at risk in case of floods. The questionnaire responses suggest that most of the systems globally were created to avoid flood damages to homes and household properties (Figure 2). Loss of human lives, and agricultural losses were the next two important motivations. Fewer FEWS were developed to mitigate industrial losses and environmental damages. Since the dominating land-use types of the target area are rural

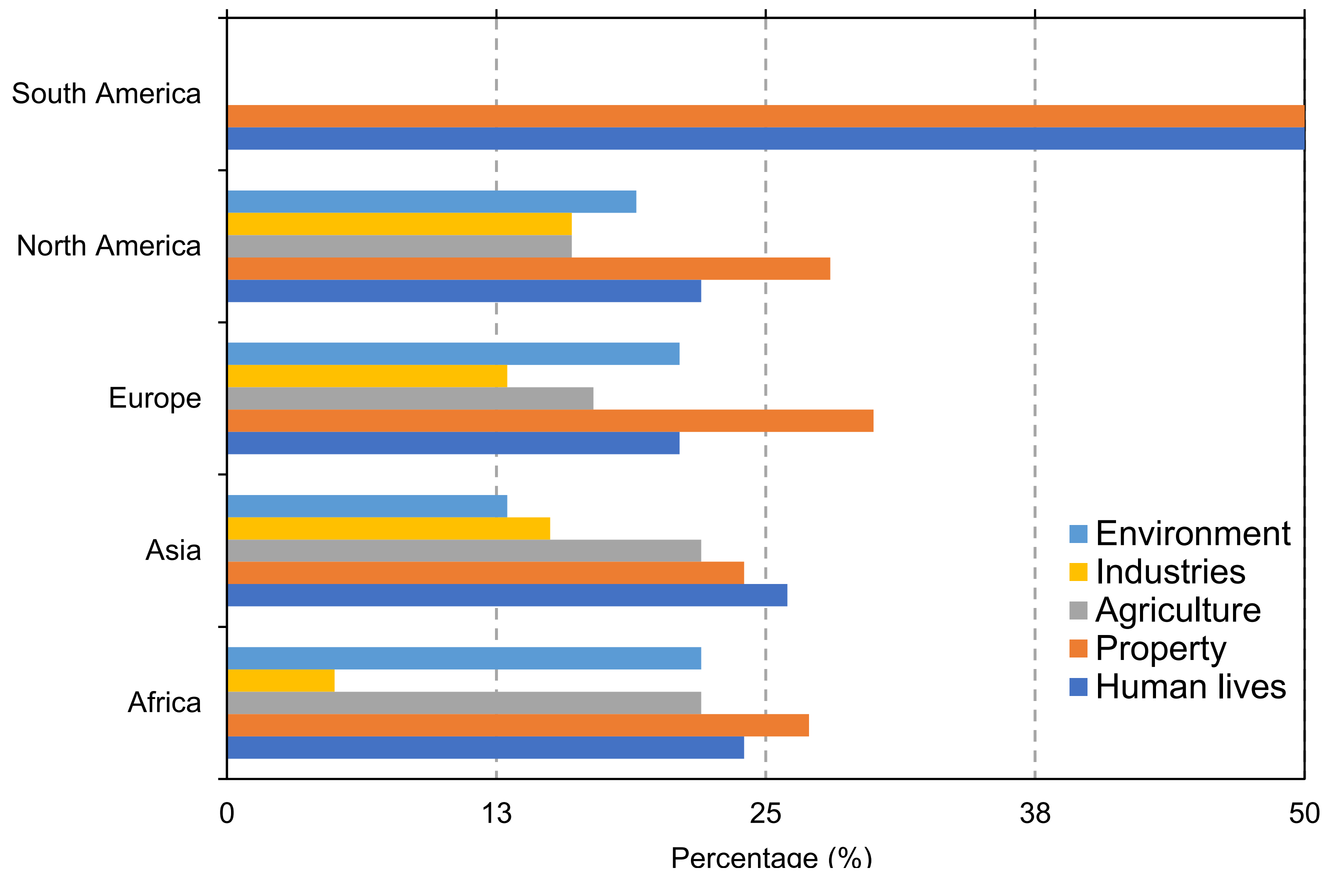


Figure 2: Main flood damages considered in implementing FEWS (%)
(Response from South America was received on only one FEWS)

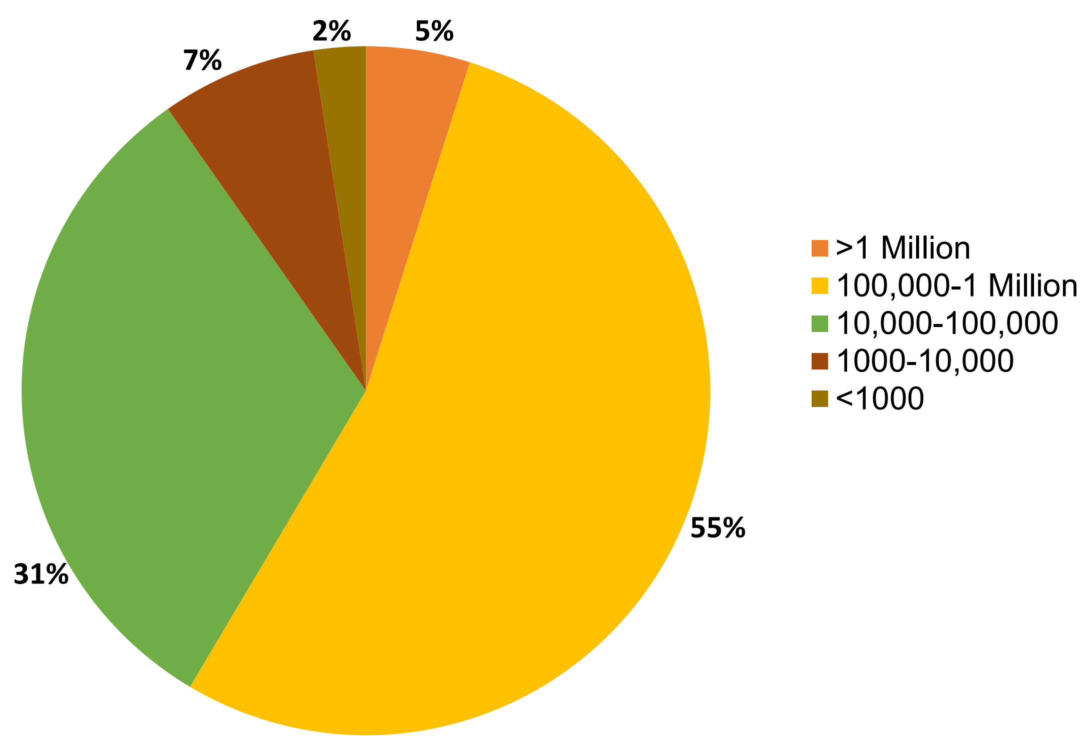


Figure 3: FEWS distribution by size of the population benefitting

and semi-rural, minimizing the agricultural damages was a primary reason for FEWS implementation. The nature of the downstream communities served by FEWS are urban (20%), semi-urban (30%), rural (27%); the rest are and a mixture of three main categories and various other land-use types. Although flood risk mapping is complimentary to FEWS, only 67% of the systems have developed flood hazard maps and of them only 30% have distributed these maps to communities under risk.

The size of the population that benefits from a FEWS is highly variable. In terms of people at risk in the downstream, 55% of the systems cover areas with 100,000 to 1 million people at risk, while 31% protect areas with 10,000 to 100,000 people (Figure 3). In Europe, FEWS are in place where the vulnerable community in the target area is 10,000 to 1 million people, while in North America, Africa and Asia, FEWS are implemented for a broader range (less than 1,000 to more than 1 million) residents at risk. This includes a handful of systems adopted in Asia, where more than 1 million and up to 10 million people reside in the target areas of FEWS. Quantitative evaluation of assets suggested that USD 1.8 trillion are at risk in a Japanese river basin where a FEWS is operational. In Nepal, the vulnerable downstream assets in two river basins are valued at over USD 400 million, while in the basins of Burkina Faso and Vietnam, more than USD 1 million of properties are in highly vulnerable areas.

Monitoring and Forecasting

Flood monitoring and warning services must be scientifically sound (UNDRR, 2006; WMO, 2011). The primary task involved in flood forecasting system include executing hydrological models with the observed hydro-meteorological data to obtain river discharges and, executing hydraulic/hydrodynamic models for predicted streamflow to simulate river stages. In some cases, geo-referenced water surface elevations are used to produce flood inundation maps, used in disaster relief operations and government-led public awareness efforts. To ensure accurate, timely early warning information, the operation of a FEWS requires sound technical capabilities for which survey responses are discussed herein, covering the topics of levels of hydro-meteorological observation systems in operation, common types of floods experienced, hydrological/hydrodynamic models used, and forecasts produced. Most of the river basins in the survey have both rainfall and water level gauging stations, of which about half are equipped with telemetric systems; the rest have either manual data recording, collection and transfer, or are semi-automated (data recording is automatic while data collection and transmission are manual). Only half of all basins have streamflow gauges, of which 52% are operated manually; of the other 48%, 38% are telemetric and 10% are semi-automated. Fluvial and flash floods are the most common types of floods experienced in the

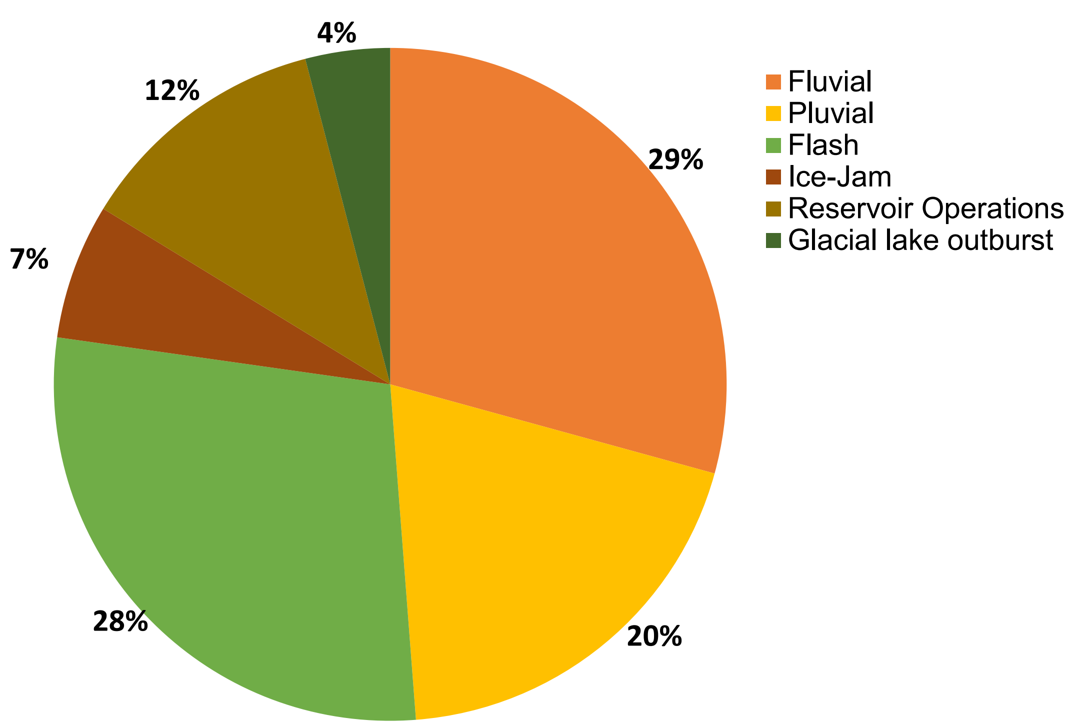


Figure 4: Types of floods experienced by surveyed FEWS

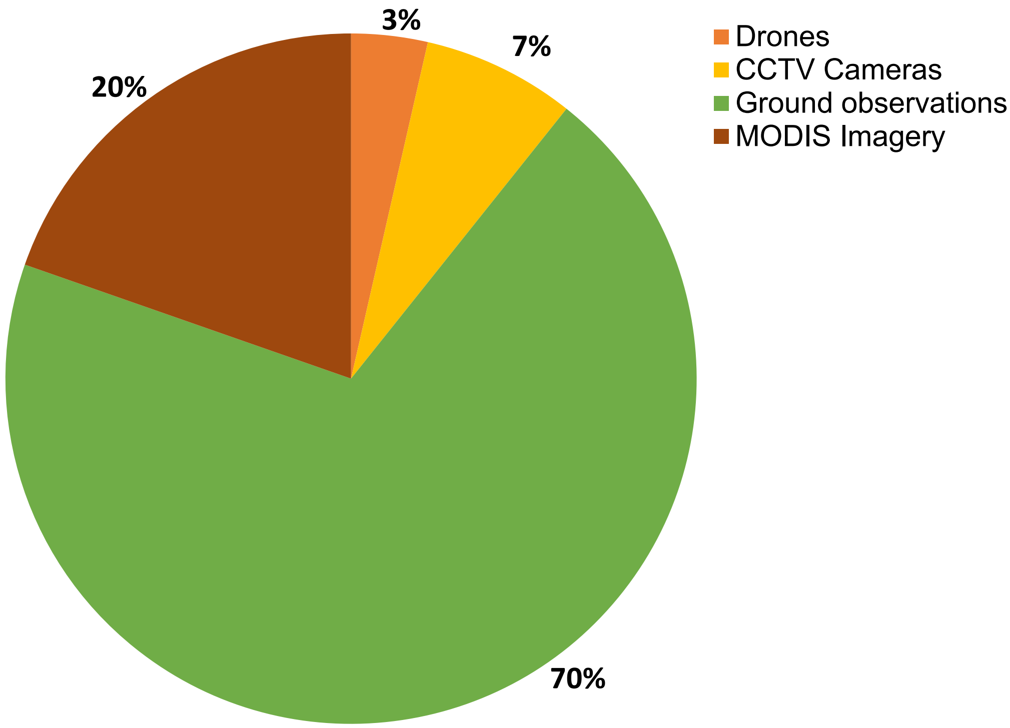


Figure 5: Flood monitoring methods

basins covered by survey responses, followed by pluvial floods and human-induced floods (caused by upstream reservoir operations) - Figure 4. Flash floods, which can be forecast but with lead times too short for appropriate action, are the major threat to human lives globally.

Although aid from satellite technology has advanced greatly, data obtained from ground observations still dominate in operational flood monitoring and warning systems throughout the world (Figure 5). Survey responses show some Asian and North American warning systems use drones and Closed-Circuit Television (CCTV) cameras for flood monitoring, whereas remote sensing data is used in other regions. The situation in South America is uncertain due to fewer responses. 49% of FFCs employ models specifically developed for target river basins due to their large variation in hydrological and climatological characteristics. Among the rest, 31% of open source models and 19% of commercial models are employed. Water level is the major output from nearly all operational FEWS followed by outputs of streamflow and inundation information that are available for almost half of the systems. Event-based flood forecasts are produced for about 40% of the basins and seasonal and continuous updates were available each for about 30% of the basins. Daily temporal resolution is the most commonly used by FFCs for continuous forecasts.

Warning Dissemination

Once the warning is generated, it is essential to communicate it to all those at risk promptly. Effective warning dissemination involves an operational telecommunication system that transmits warnings from the FCC to local/national governmental authorities and to communities at risk, following the national protocols (UNDRR, 2006). Surveyed FEWS disseminate warnings generally through "top-down approach" including receivers such as Disaster Management Agencies (DMA) – national, regional, districts and townships, local and central governments, security forces such as military and civil authorities, media organisations including newspapers, TV and local radio stations, website updates, emergency service departments, related chief technical operators including water resource managers and reservoir operators, and local and international non-government organisations involved in flood risk management, which then help convey the warnings to communities under flood risk. Advanced systems such as nation-wide emergency alert systems, which push notifications *en masse* to people at risk, are in place in developed countries but all flood-prone developing countries have yet to create such harmonised systems. Flood-prone Nepal has a mechanism that conveys bulk Short Messaging Service (SMS) directly to communities under risk at local and district level; however, it also

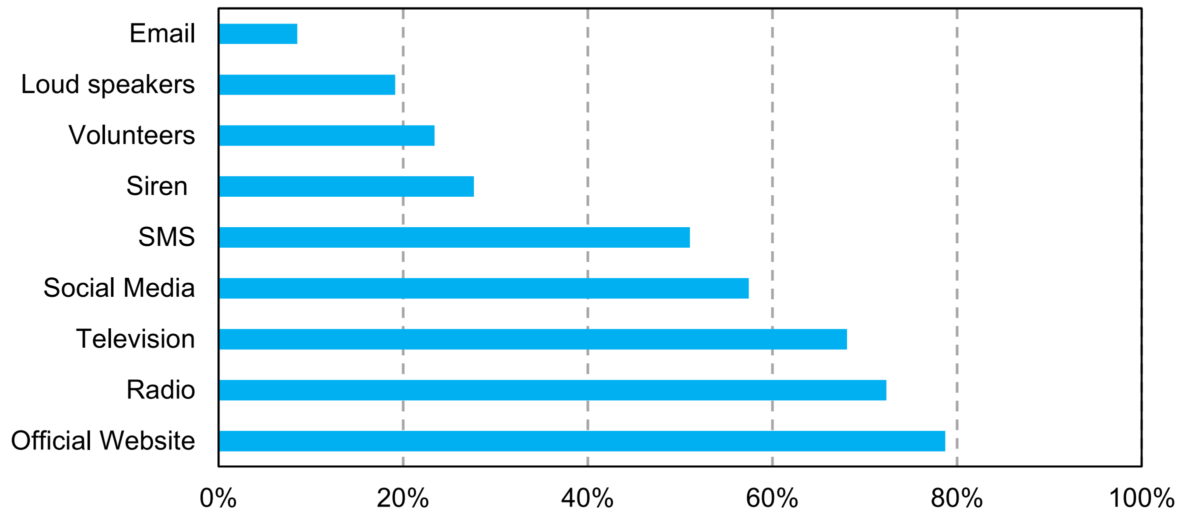


Figure 6: Warning dissemination methods used by survey respondents (%)

uses conventional ways such as handheld megaphones, loud speakers and sirens. Sri Lanka, on the other hand, recently initiated a Disaster and Emergency Warning Network (DEWN) to disseminate early warning via mass and customised SMS throughout the island nation (GSMA, 2015). Responses suggest that systems widely use official websites as a medium for warning distribution by publishing flood bulletins and alerts on webpages, followed by radio, television, social media, SMSs in descending order of use (Figure 6). Nearly a quarter of the systems involve community warning dissemination, including sirens, volunteers and loud speakers. The minimum and maximum delay between the flood forecast and warning issued is in the range of minutes to days but most of the FEWS have a delay from several minutes to hours. Delay in terms of days can be partially attributed to this: 22% of the FFCs require permission from political authorities to issue a warning. Daily and hourly updates are available from 55% of the FEWS, while others provide updates depending on the level of flood disaster. However, 7% of them do not provide continuous updates after a flood warning is issued.

Response Capabilities

Community acceptance and responsiveness to early warnings are essential in effective end-to-end early warning systems. This requires building local and national capacities through systematic training and education, implementing disaster preparedness plans and community awareness programmes led by disaster management authorities (UNDRR, 2006; Smith et al., 2017). Survey findings suggested that information on the responders' end, about community response and preparedness (e.g. preparedness to evacuate or preventive measures) is particularly lacking. To illustrate, about 42% of the responders do not have information about community response rates. For the rest that have such information, about 29% of the FEWS have response rates below 50%. Also, 13% of the systems have response rates between 50% and 70%, and about 7% of the systems have response rates between 70% and 90%. Community response rates of above 90% are obtained for 9% of the FEWS.

Community-led volunteer groups are more commonly found in downstream target areas in a flood event to support evacuation. Measures such as stocking sandbags or similar products, and flood proofing houses are undertaken by 50% and 30% of surveyed FEWS downstream communities respectively. Preparedness in terms of a checklist to be followed during an emergency evacuation is provided to target communities only by half of the FFCs. Public awareness campaigns such as trainings, seminars, TV and radio advertisements, posters to convey messages about preparedness and reaction to warnings are undertaken by almost 50% of the FEWS. Mock drills are also practiced by half of the operational FEWS to test awareness about evacuation procedures of the downstream communities.

Investments in and benefits of FEWS

Investments

To implement an operational FEWS, considerable investment is required irrespective of the country's economic strength. The investments vary, however, according to the type of operational system.

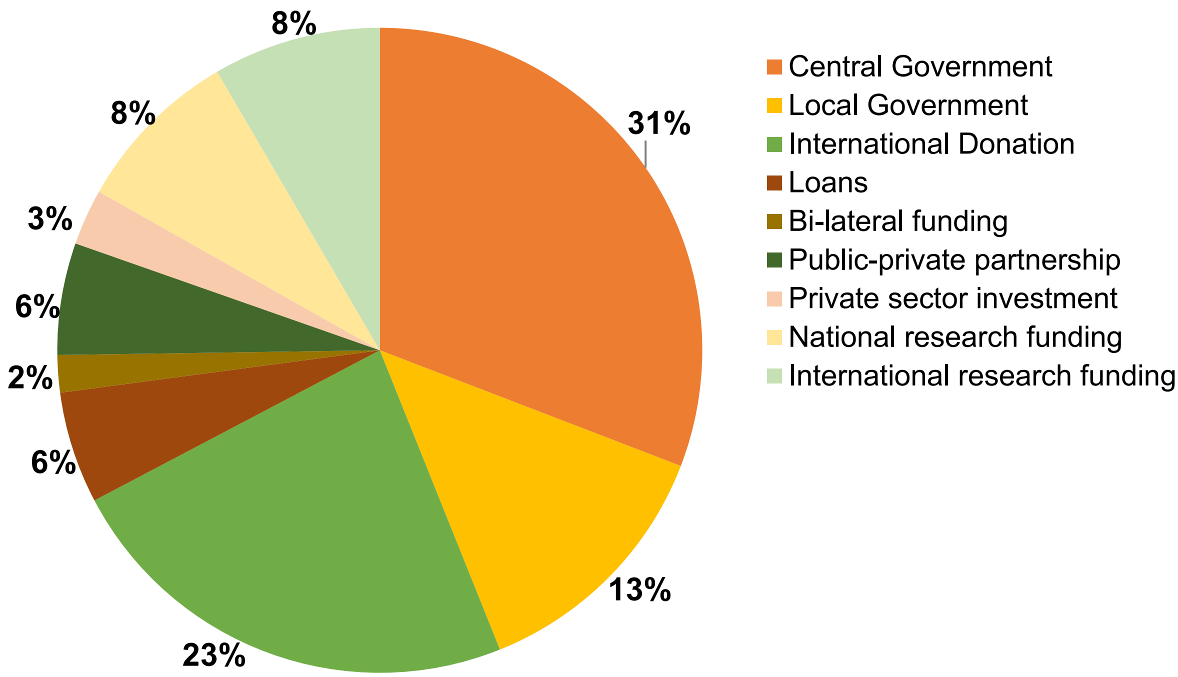
Existing FEWS were funded through various sources, including local, provincial and central governments, international agencies and donors such as World Bank, International Monetary Fund , US and UK Agencies for International Development, Asian Development Bank, African Development Bank, European Union, United Nations Development Programme, Global Environment Facility, Japan International Cooperation Agency, public-private partnerships, private sector, NGOs focused national or international projects, and others. Globally, the major sources of investment are from central governments and international donors accounting for about a third and a quarter of the investments for implementing operational FEWS (Figure 7). International donations have relatively higher share in investments due to lack of financial strength of national governments to finance and maintain FEWS. National and international research funding together make nearly 16% of the funding, while local governments contributed around 13%. The rest of the financial support is provided by loans, public-private partnerships, private sector and bilateral sources.

A notable difference between investments in developing and developed nations is that, counter-intuitively, fewer sources of investments exist for developed countries than for developing countries. For instance, developing economies in Asia and Africa receive financial supports for FEWS implementation and operation from almost all the sources mentioned above, whereas investments for FEWS in Europe were obtained from governments, international donors and loans only. The largest investment in FEWS from local and central governments are in North America (Canada), with smaller funding obtained through international donors and loans (Figure 7).

Since effective operation and maintenance of FEWS involve multiple components, stakeholders, and agencies, it is difficult to accurately ascertain the total amounts invested in the development, implementation, operation, and maintenance costs of FEWS. Only a small fraction of the respondents provided quantitative information about how funds are invested in FEWS. Despite the scarcity of the data, some conclusions can be drawn. The inequality in the amount of funds invested in developed and developing economies to establish and operate FEWS is significant. To illustrate: the grant provided to develop the FEWS in West Africa's Niger River basin, which spreads through nine countries and covers a surface area of about 1.5 million km², was USD 4 million (USD 3 million from Dutch Agency for international cooperation (NL EVD International) in 2014 and USD 1 million from African Development Bank in 2017. The amount invested to develop a FEWS for the Danube and Vistula river basins in Slovakia is almost eight times higher (USD 34 million) while these two basins only cover a 49,000 km² area (about 3% of the size of Niger river basin). Due to higher investments, Slovakian river basins have advanced FEWS to protect 5 million residents in the downstream whereas the Niger river basin only has basic FEWS to protect 20 times more people — 100 million.

In Canada, flood forecasting is a provincial responsibility. Each province has its hydrological center in charge of flood forecasting and warning. In Ontario, some conservation authorities also deliver flood forecasts at the municipal level. Most FEWS, therefore, are funded from provincial or municipal budgets. As an example, the New-Brunswick FEWS were set-up and funded by the province. Similarly, the province of Quebec has set up FEWS since the 2017 spring floods in the Montreal region. The province of Manitoba has started setting up FEWS, which should be operational by the end of 2019. Investments in FEWS vary from one province to another but tend to rise after major flood events (Zahmatkesh et al., 2019).

Investments in implementation of FEWS (based on responses to the survey) in developing and least-developed nations range from USD 5,000 in Namibia to USD 5 million in Myanmar including USD 100,000 in Nepal for an intermediate system, USD 1 million in Cambodia and USD 2.5 million in Bangladesh for advanced systems. These investments are the tip of the iceberg since various international efforts are underway to increase both funding and local capacity for generating and communicating effective warnings in least-developed countries and small island developing states (SIDS). This includes the World Bank-managed Global Facility on Disaster Reduction and Recovery (GFDRR) that implements the Climate Risk and Early Warning Systems (CREWS) initiative with support from WMO and UNDRR. CREWS, launched in 2015 to assist in achieving Sendai DRR targets, has been supporting 19 LDC and SIDS financially by investments of USD 17 million and leveraged additional USD 106 million funds in 2017 alone (CREWS, 2017). Further, its objective is to mobilise USD 100 million by 2020 to support DRR to its maximum capacity. It is worth noting that funding for GFDRR this decade was USD 88 million — double the USD 44 million invested in the previous decade (Sparks, 2012). Even though this amount refers to hydro-meteorological disasters, a considerable share of these investments is thought to have contributed to FEWS as floods are the most frequent global WRD. To enhance local early warning, response and damage assessment for disasters including floods, United Nations Economic and Social Commission for Asia and Pacific (UN-ESCAP) provided USD 1 million worth spatial data, products and services to its member states through international and regional initiatives since 2017 (United Nations, 2018).



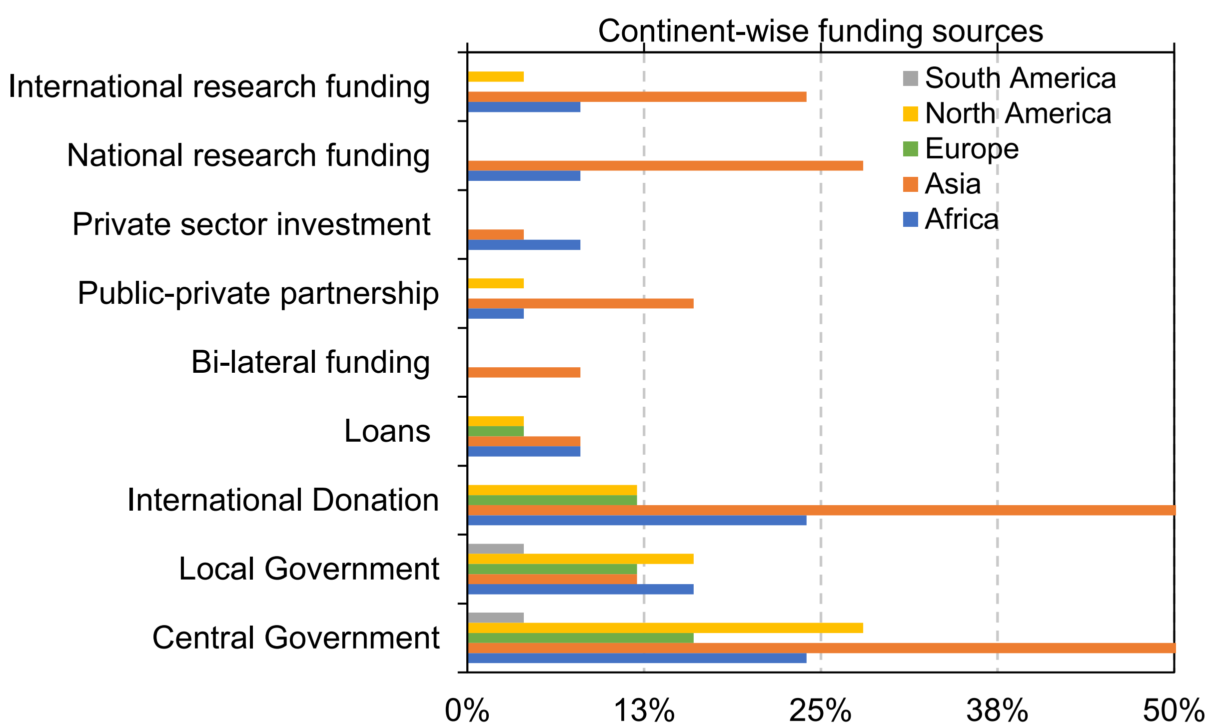


Figure 7: Global (top) and continental (bottom) distribution of investments in FEWS

Benefits

Evaluating benefits of FEWS is crucial and can be carried out by examining trends in flood disasters and its impacts on economy and mortalities during post FEWS implementation and operation. According to the survey, from year 2000 to 2017 inclusive, the number of FEWS has nearly doubled. Because FEWS effectively mitigate flood risk impacts, the increase in their number, combined with structural and non-structural measures, likely contributed to the decline in flood disasters — from 157 in 2000 to 126 in 2017, and reduced the mortality rate by 45% — from 6,025 deaths per annum in 2000 to 3,331 deaths in 2017 (Figure 8). However, other influential factors such as changes in exposure, climatic variabilities in some regions, and migration out of flood-prone regions, also had significant impact on the disaster statistics above.

Further, individuals affected by floods in 2000 were 73 million, which reduced to 55 million by 2017 — a roughly 24% reduction. To illustrate, the 18-year average for casualties due to floods globally (2000-2017) is 5,368, with 3,331 recorded causalities in 2017 — some 2,000 fewer human lives lost than average. Since several billions of dollars are invested in FEWS, an analysis of whether benefits outweigh the expenditure is essential to financially support increasing availability of FEWS in both developing and developed nations. Cost-benefit ratios could vary due to many factors, such as technological advancements in FEWS, economic value of the target area, level and exposure to flood risk, magnitude of flood disaster, operational efficiency of the FEWS, structural measures employed parallel to FEWS, methods/models utilised to estimate benefits, and others. The literature suggests a wide range of cost-benefit ratios for operational FEWS. Pappenberger et al., 2015 estimated that in Europe, over 20 years, every Euro invested in European Flood Awareness System (EFAS) returned 159 Euros in a baseline scenario, 202 Euros in an improved forecast accuracy scenario, and 409 Euros if avoided damage factors were varied in another scenario. Avoided damages due to early warning can lead to benefits of ~ USD 559 for each dollar invested in flood-prone region of Bangladesh over 10 years (Subbiah et al., 2008). In 2015, Arias et al. conducted a cost-benefit analysis in the Philippines that revealed cost-benefit ratio of 1:33 can be reached. A case study on urban flood warning systems in Australia revealed a six-fold return on every dollar invested (UNDRR, 2004). In a developing country like Fiji, economic analysis suggested that every dollar spent in early warning of floods in an optimal scenario will lead to a return of USD 7.3 and in modest case, provided a return of USD 3.7 over 20 years (Holland, 2008). Estimating the monetary benefits of upgrading the hydro-meteorological system and early warning capacity of developing countries to developed countries' standard would yield cost-benefit ratios of between 4:1 and 36:1 according to Hallegatte, 2012. Global flood-related financial losses over 2000-2017 were USD 27 billion, of which even if most conservative approach is considered i.e., 1% reduction in losses through early warnings, then also significant savings of USD 270 million can be attained.

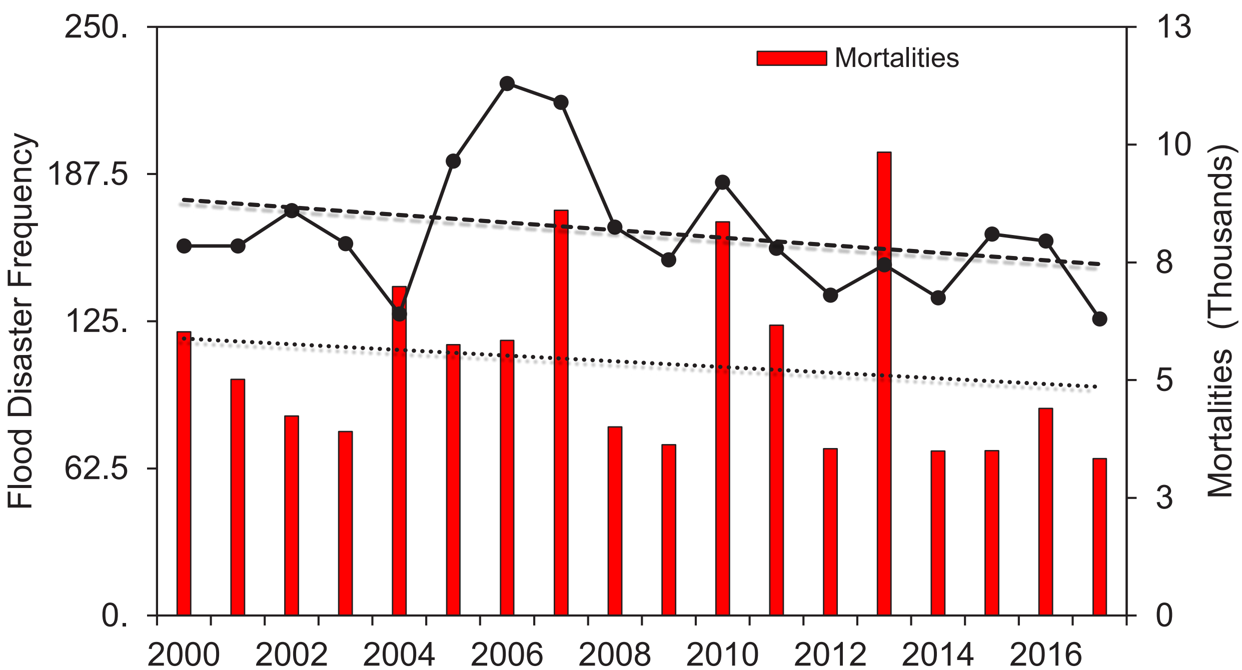


Figure 8: Trends in flood disaster occurrences and impacts – Global (Data source: EM-DAT 2018)

Avoided damages due to FEWS

Floods induce severe monetary losses that can impede the growth of countries, especially low- and middle-income countries. Therefore, reducing the ratio of disaster losses to Gross Domestic Product (GDP) is of the utmost importance. It is one of the targets of Sendai Framework. It is also a critical component to SDG 11.5 that aims to reduce significantly the number of people affected, even killed, and the direct economic losses caused by water-related and all other disasters, with a focus on protecting the poor and people in vulnerable situations. Figure 9 depicts current (2000-2017) flood disaster losses as a percentage of GDP loss for selected high-income (Canada and France), upper-middle-income (Peru and Russian Federation), lower-middle-income (Bangladesh, Indonesia, Philippines, and Nigeria) and low-income (Niger) countries. The GDP loss is the percentage of annual flood-related economic losses to the GDP of the same year of each selected country (Wallemacq and House, 2018). The calculated annual percentages shown in Figure 9 were averaged for the period of 2000 – 2017. The most notable difference between high income and lower-middle-income countries is that despite higher economic losses of the order of USD 1 billion, high-income countries revealed a negligible loss in GDP. Lower-middle income countries, on the contrary, have lower economic losses but these losses represent a higher percentage of their GDP. For instance, the Philippines and Nigeria have economic losses of about USD 131 million and USD 46 million, and their relative GDP loss also dropped about 0.07% and 0.01%, respectively. However, Indonesia has a relatively lower percentage of GDP drop than monetary losses. An identical trend can also be observed in upper-middle-income Russia having 0.03% GDP loss for USD 482 million worth economic damages. The hardest-hit country in terms of GDP loss is Niger (i.e. low-income country) with the lowest financial loss of USD 70 million and the highest percent GDP loss — more than 0.9%. Bangladesh (i.e. a lower-middle-income country) and Peru (i.e. upper-middle-income country) are the second and third highest affected countries according to GDP loss in proportion to the economic losses among the countries evaluated in this study, respectively.

Furthermore, flood-related GDP losses for Niger, Peru, and Bangladesh are considerably higher than the 0.5% threshold for major economic disaster set by the IMF. Overall, apart from Peru, high-income and upper-middle-income countries experience relatively low economic impacts from flood disasters, whereas the highest burden is placed on low and lower-middle-income countries. In the situations where the flood risk mitigation strategies are efficient and effective - i.e., operational efficiency of FEWS is optimal with proper structural measures in place and timely actions are taken - the economic damages of flooding are minimised.

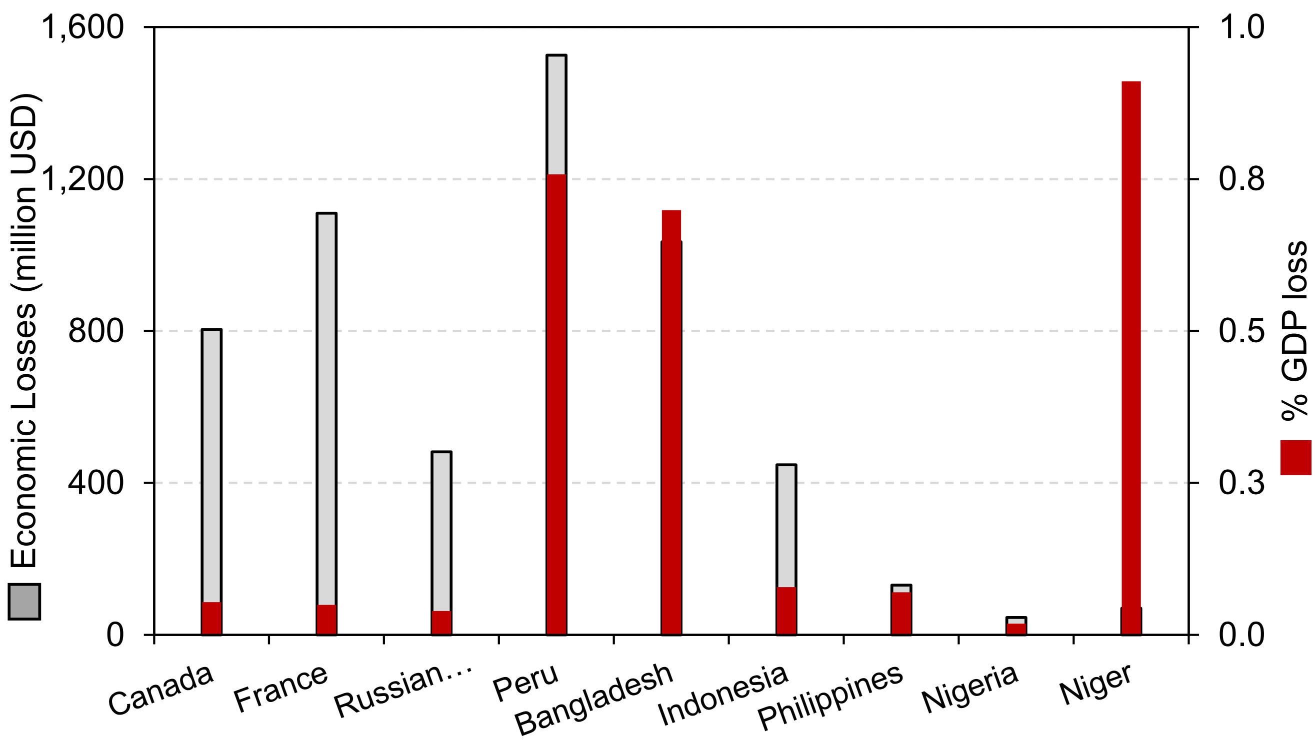


Figure 9: Flood disaster economic losses compared to GDP losses (Data source: EM-DAT and World Bank);

CHALLENGES AND PROSPECTS OF FEWS

Challenges

Technical challenges

There are various technical challenges at national, regional and local levels to operating FEWS: data collection and integration, synthesis, management, the hydrologic modeling process, and, warning dissemination and communication networks, among others. FEWS in the developing world lags in terms of integration of ground records, remotely sensed data, integration of Numerical Weather Predictions outputs for generating forecasts as well as risk knowledge information. Firstly, inadequate hydrological network coverage for monitoring of floods i.e., un-gauged or poorly gauged sites, adds to inaccuracy of flood forecasts. Globally, 75% of the flood forecasters (based on this study) indicated that their river basins are equipped with insufficient gauging stations for rainfall, water level and streamflow observations. 50% of the FCCs that responded revealed that their measuring equipment, gauges and data transferring instruments have deficient technology.

Inadequate and poor management of hydrological networks and/or temporary shut-down due to equipment damage, weather-related or financial issues impact subsequent challenges such as discrete and short records of data, poor data quality, and modeling-related uncertainty. Multi-decadal continuous data records are required for producing robust flood models, model forecasts, and hazard map preparation. Only 25% of respondents indicate that FEWS are equipped with back-up units in case of breakdown of the existing measurement units. Measurement errors also affect data accuracy. The acquisition of spatial data required for flood forecasting and risk mapping - such as land-use, population distribution, or soil moisture - are problematic, as some of these data sets are not updated regularly enough to be compatible with flood forecasters' needs. Spatial data products, although accessible freely and available in near real-time, are under-utilised by FFCs; ground observations remain the common practice to detect floods. Using remotely-sensed data for real-time flood forecasting requires high-performance computing resources for data management and integration, model simulation, and further processing which will, however, necessitate more investments in FEWS. For instance, the detection of flash floods remains a major challenge even though this kind of flood can be detected using real-time rainfall observation (e.g. meteorological radars) and real-time upstream water level information. The technology is not available everywhere, not even in few developed countries. Another common technical issue is the performance of the models used for flood forecasting. In operational flood forecasting and warning, modeling related challenges involve improving the accuracy of forecasts by accounting for uncertainties in input data, modeling approaches, model simplifications, and the output quantification. However, nearly half of the flood forecasters (survey responses) mentioned that the models they use for producing early warnings are not accurate or advanced enough for the purpose. Forecast hit rates varied for different systems and river basins. The error or false alarm can affect the magnitude and timing of floods simulated, leading to missed warnings of flood disasters. The longer the flood warning lead time, the smaller economic losses will be, but the uncertainty of such forecasts is higher. Further, there is an obvious need to evaluate operational effectiveness of flood forecasting system frequently in order to assess if upgrades and improvements to the modeling tools and strategies are required or not. Although it is crucial, according to survey respondents, only a third of the FEWS were evaluated technically.

One of the major challenges faced by operational systems is the lack of technical expertise and manpower. Trained personnel with flood forecasting expertise and adequate forecast group staffing are required by the FFCs to effectively issue timely warnings. However, 74% of the flood forecasting personnel confirms that their centers do not have the experts and staff capable to integrate data, perform forecasts, and disseminate information. This can be partially attributed to fewer specialised experts in the employment sectors and higher work load for rescue and post-disaster activities during major flood events (Alberta WaterSMART, 2014). In developing countries, the lack of investments in personnel and the absence of dedicated permanent staff is a major limitation to the proper operation of FEWS. Overall, the survey responses suggest that forecasters primarily possess technical know-how but lack knowledge of flood vulnerability assessment, warning communication, and downstream response capabilities, including evacuation preparedness.

Financial challenges

Many technical issues faced by operational systems relate to financial challenges. Owing to funding limitations, sustainability of FEWS is a major challenge that leads to discontinuous operation of warning systems, fewer funds for upgrading or advancements, and insufficient recruitment and training of FFC personnel. Even though UNDRR (2006) necessitates FEWS to operate monitoring and warning services continuously to generate timely warnings, 55% of the FFCs surveyed do not have funding to meet that requirement and 66% lack adequate operational funding. Further, nearly 50% and 66% of responders state that budget is not available for modernizing the systems and personnel recruitment and training. Funding restrictions are more pronounced in developing and least-developed countries reflecting their economic development level. For instance, over 75% of the survey respondents from FFCs in Africa indicated lack of sufficient investments for overall maintenance and operation of FEWS whereas this percentage dropped to about 40% for Asia. Limited funding support is the reason behind many African river basins having "basic" but not "intermediate" or "advanced" FEWS (Figure 1). This means that although advanced hydrologic models and data are available to African systems, they would still require funds to establish observation networks, high-tech computers, and skilled well-trained personnel to use them operationally.

Other considerable challenges involve lack of information on cumulative, annual and individual costs for implementation, operation and maintenance of FEWS. Owing to the multi-agencies involved and multi-disciplinary components of FEWS, complexities arise in estimating investments of operational flood warning systems. This is evident in survey responses where over 90% of the responders were unable to provide an exact amount of total FEWS investments. The complexity rises when multiple donors contribute to total investments for many disasters from which investment into floods must be separated. For instance, in most cases monitoring portion of investments are combined for hydro-meteorological disasters that include storm, floods, cyclones, droughts and others aiming a multi-hazard early warning approach.

Furthermore, analysis of the impacts/benefits of FEWS is necessary to justify tremendous investments; however, this information is not nationally and widely reported. This is basically due to a lack of national disaster-related databases for monitoring the progress of global Sendai targets, such as the reduction in mortality, people affected, economic loss, etc. Self-reporting by each country on impacts of flood disasters is vital since world's most comprehensive disaster database, EM-DAT, indicates under-reporting of disasters by African countries, which are vulnerable, at high-risk, and least developed (Wallemacq and House, 2018). However, in 2018 UNDRR initiated Sendai Framework Monitor encouraging the member states to record and report disaster-related data to monitor the progress in achieving Sandai targets (https://sendaimonitor.unisdr.org/). For donors to make informed investment choices, such a database is of primary importance. Quantitative assessments of investments and benefits can aid in gaining insights into economic impacts of these systems.

Institutional challenges

Once a warning is issued, a significant challenge exists to communicate the information to the authorities/municipalities caused by a lack of coordination between the technical institutions generating warnings and communicating agencies assigned to alert the public in the absence of dedicated communications officer in FFCs. The problem is compounded by ineffective data dissemination approaches among multiple agencies. Alberta WaterSMART, 2014, for instance, mentioned that during a flood event in Canada, flood forecasters devoted 30 hours in a 48-hour period informing municipalities and local authorities of the flood warning. Warnings must be conveyed in a timely manner, particularly in vulnerable and remote locations, should use clear information expressed in non-technical language, identify and mention areas at risk, explain potential losses within various timeframes, and provide information to reduce losses through use of response plans (UNDRR, 2006). However, due to a lack of Standard Operating Procedures (SOP) from national to local levels, warnings issued in many places are generally technical, inconsistent, and incomplete, leading to misinterpretation of warnings and inadequate responses. This is evident in Cambodia where Dutta et. al., (2015) assessed the gaps in early warning systems for hydro-meteorological disasters and found that people-at-risk were unable to interpret warning information effectively, in most cases. Limited mandate and capacity are another weak area, needed to be considered as institutional challenges in FCC.

Social challenges

Even with an efficient FCC, losses will only be maximally mitigated if the communities at risk have adequate infrastructure to receive warnings. Survey responses suggest over 55% of the responders agree that communities do not have equipment required to receive warnings. This is more challenging when dealing with flooding of coastal areas — the areas in least developing countries where most vulnerable and poor people reside, and where individuals at risk typically lack access to basic amenities. According to the survey, even when a warning is conveyed appropriately, often it isn't heeded; survey respondents estimated that only ~52% of the people in such circumstances find flood alerts credible enough to respond. All people at risk must be prepared to take appropriate actions and respond immediately. However, survey respondents estimate a community response rate is 57% and preparedness is inadequate. Further, knowledge about distinct responsibilities and role of different agencies, risk awareness and response plans during emergencies are particularly lacking among the public. This is partly because of ineffective strategies in place and irregular organisational awareness programs, such as drills, seminars and trainings in preparedness and evacuation procedures, compounded by low literacy rates in highly-vulnerable communities in developing and least-developed countries. The problem of low response to warnings escalates when the target area communities include a higher proportion of elderly people or children who are less aware and dependent on others to make decisions and respond. Failure to respond promptly to flood warnings can render efforts in closing the technical and financial gaps futile.

Prospects

Despite the challenges outlined, many opportunities exist to improve FEWS. As climate and the weather cycles continue to change, it may be expected that countries will seek to upgrade their FEWS from basic to advanced, taking advantage of the availability of tools that provide better quality data in real-time, access to global flood forecasting systems to supplement national FEWS, better computing techniques and resources, and new communication channels for better connection with end users. The prospects discussed in the later sections are a result of consultations with the experts in relevant fields.

Improved data quality and availability

There have been significant technological advancements in the collection of data for monitoring and forecasting of floods across the globe. These developments include the increasing availability and coverage of various ground as well as remote sensing data such as satellite imagery and radar-based data accessed in real-time or near real-time, finer spatial and temporal resolution data (Thorndahl et al., 2017), the availability of Numerical Weather Predictions models' outputs to apply in hydrologic models (Yu et al., 2018), and the availability of seasonal forecasts to supplement short term forecasts. Applications of these techniques can help FFCs to improve the accuracy of flood predictions and thus enhance and strengthen their early warning systems.

Furthermore, to improve the efficiency and reduce time lags, FFCs may consider better data management systems that involve shifting from manual data collection and transfer systems to telemetric mechanisms that can help in maintaining long records of continuous data. International data-exchange policies and procedures are likely to be in place among countries sharing transboundary river basins to enhance proactive data and forecast sharing from upstream to downstream locations. Since different agencies are involved in data collecting and monitoring processes in a transboundary basin, the coordination and co-operation among agencies are expected to strengthen and become more transparent. Early warning lead times are expected to increase, providing downstream residents greater time to prepare, evacuate and respond and to reduce economic damages by transferring moveable assets, livestock and tools to a safe place. Increasing lead time can be achieved with the application of advanced modeling approaches, tools and methodologies, for instance, by using probabilistic approach in the FEWS as used by Smith et al., 2017.

Several initiatives around the world seek to at least reduce that gap. An example is the CREWS initiative, which aims significantly increase the capacity of LDCs and SIDS by integrating some of these existing advanced technologies and methods into "basic" FEWS by the end of the SDG period in 2030. Another one is International Flood Initiative (IFI) (http://www.ifi-home.info/). It is a joint initiative of international organisations such as UNESCO-IHP, WMO, UNDRR, UNU, IAHS, IAHR and ICHARM. IFI focuses on research, information networking, education and training, empowering communities and providing technical assistance and guidance through the Platforms on Water Resilience and Disasters in several developing counties. The Platform on Water Resilience and Disasters connects the demand for sound, timely decisions and actions made by policy-makers and local communities with the provision of disaster risk information generated from integrated risk assessment and risk change identification. The platform also strengthens stakeholders' risk management capabilities and promotes the active use of interdisciplinary and transdisciplinary approaches. The platform activities are currently initiated and underway in Sri Lanka, Myanmar, Pakistan, and the Philippines and development of an advanced FEWS is set to the top-most priority.

Access to global flood forecasting systems

Since the basic FEWS systems in most LDCs are often ineffective in an emergency, future initiatives should include ensuring that disaster-prone LDCs have financial and technical capacities to apply global level "advanced" flood monitoring, forecasting and warning services and update their modeling approaches. These involve Copernicus Emergency Management Systems' (EMS) Global Flood Awareness System - GloFAS (http://www.globalfloods.eu/), which complements the national and regional flood monitoring and forecasting, and WMOs' Global Telecommunication System (GTS) for disseminating hydro-meteorological data, forecasts and alerts to all the member states. GloFAS is a new (2018), freely accessible system with 30-day and seasonal forecasts. Finer scale forecasts i.e., local forecasts, are not generated within the system. For LDCs to use GloFAS at higher spatial resolution, these systems must be adapted to the basins in disaster-prone LDCs. Many advanced global or national scale systems use "big data" in remote sensing as inputs to the hydrologic/hydraulic models and, since these data require expensive high-performance computing (HPC), most regional and local scale systems tend not to use these data operationally. Progressing further, for major basins that are un-gauged, "big data" as data cubes will prove to be an economic asset because initial investments are costly but will yield long-term benefits outweighing the costs. Google Earth Engine (https://earthengine.google.com/), Amazon Earth (https://aws.amazon.com/earth/) and EarthServer (http://www.earthserver.eu/) are among the entities providing free access to some of these big datasets for LDCs. HPC will be accessible in LDCs through public-private-partnerships. Initiatives enabling access of such computing through this mechanism include NASA and Google Earth Engine working with national disaster management authorities through SERVIR in Himalaya, Mekong, Amazon and Africa (Markert et al., 2018). SEPAL, a cloud computing-based platform developed by FAO and partners, is available to LDCs as high processing computing resource (Tondapu et al., 2018). Earth Observation Data and Processing Platform (EODPP), developed by the Joint Research Center (JRC) of EU, is providing speed access to processing data flows originating from the EU Copernicus program (Soille et al., 2016).

Better risk computing techniques

The research community is constantly developing improved forecasting methods that are being adopted in operational flood forecasting. Examples include the use of ensemble forecasts, multi-models and data assimilation to reduce predictive uncertainty, and probabilistic forecasts to address inherent uncertainty in the hydrologic modeling process. Artificial intelligence (AI) and data mining techniques are increasingly being used for vulnerability assessment (e.g. analysis of satellite images to identify communities at risk), but also for risk calculation (Saravi, et al., 2019).

These developments are only partly integrated in operational FEWS, even in the developed world. For instance, ensemble, probabilistic, and multi-model forecasts, which only became popular in the developed world in the last decade, are still the subject of intense research. It is anticipated that these techniques will become more available to underdeveloped countries as they mature. Development in distributed computing services (e.g. cloud computing) will make data and CPU-intensive methods accessible to all FEWS.

Better risk communication to end users using ICT

Individuals are becoming more technology-bound than ever before due to smart phones, the internet and social media, all being integrated into warning dissemination systems by FFCs and disaster managers worldwide. This will lead to more people acting as disseminators - receiving and spreading timely warnings widely via electronic and social media channels. Eventually, communicating flood advisories and posting information about response plans and checklists, evacuation procedures and locations, and related updates on social media and web interfaces are expected to become a formal part of warning communication and response preparedness. As the interaction between downstream communities and FFCs, disaster managers improve, acceptance of flood warnings and response rates would intensify, which will prepare communities to make risk-informed choices. Further, communication of flood warnings is projected to be tailored to the needs of particular communities, especially least-income vulnerable people with low literacy rates in Africa and Asia.

CONCLUSIONS AND RECOMMENDATIONS

Floods are among the most devastating WRD experienced throughout the world. Their cost to the global economy is significant and continuously increasing. To reduce flood risk and impacts, FEWS have been implemented in many parts of the world, but consolidated information is lacking on the nature of FEWS, investments to implement and operate them, the benefits that can be attributed to them, as well as challenges and prospects associated with them. This report has attempted to start addressing these gaps, particularly in developing countries but considering developed countries as benchmarks where applicable. For this, a literature review and detailed survey targeting local and regional institutions dealing with flood forecasting and early warning services was conducted in 2018.

The survey questionnaire included 84 questions covering the range of the above-mentioned gaps. For the purpose of the study, FEWS were categorised into basic, intermediate and advanced, depending on whether the four components (risk knowledge, monitoring and forecasting, warning dissemination and response capabilities) of FEWS exist, and how comprehensive they are. The questionnaire is available online and can be useful in its own right, for example for more in-depth regional surveys, in its current or modified form. In total 53 countries responded to the survey, of which 47 were developing. Operating within the 47 developing countries are 42% of the intermediate FEWS were and 42% of the advanced FEWS. Asia has more high-tech monitoring, forecasting and warning dissemination systems than Africa. International financial support — on the order of USD 100 million — is available to create more advanced FEWS in developing countries. However, obtaining funds for staff training and long-term operations of FEWS is challenging.

The direct identification of benefits of FEWS from existing sources is difficult. An indirect measure of their benefits in the 2000-2017 period is the declining global trend in flood disaster damages and causalities (EM-DAT, 2018). While this may be attributed to various DRR efforts, it should be noted that the FEWS implementation rate has been significant: 50% of the FEWS surveyed were established over the same period. In countries affected by flood disasters, the cost-benefit ratios mentioned in the literature range significantly depending on local context, i.e. ratios ~1:33 ~1:400 and ~1:560 were quoted for the Philippines, Europe and Bangladesh respectively. In terms of the ratio of flood disaster losses to GDP, lower-middle-income and low-income countries appear to be the hardest-hit as lower economic losses represent higher percentage of their GDP. At the same time, in high-income countries. higher flood-related losses accounted for a negligible percentage of their GDP.

Overall, the current state of FEWS make the achievement of global DRR targets by 2030 uncertain, especially in most African countries and some Asian countries, due to many technical, financial, communication and social challenges faced by FEWS development and operation. To overcome these challenges and achieve the targets of global development agendas, international agencies, flood forecasting centers, local and central governments, policy makers, risk managers, NGOs, and communities at risk must work together.

The current study of the status of FEWS only touched the surface, and naturally has its limitations. While the attempt was to cover the globe, the number of responses to the survey has been limited (partially because of existing institutional restrictions on information sharing, partially due to lack of capacity or incentive to respond). Categorisation of FEWS adopted in this study may overemphasise technical aspects of FEWS over community involvement. Analysis of benefits and investments has not been comprehensive due to the lack of information identified in literature or received from the survey. The possibility of biased responses naturally cannot be ignored, and direct interviews would be the best option to minimise such a bias.

At the same time, all the above limitations effectively reflect the gaps of our current knowledge on FEWS, which may not be addressed at once, but could form an agenda for action in this specific domain for the future. To improve the global knowledge on FEWS status and progress, the following recommendations are put forward.

- Investments made into development of all components of FEWS need to be better coordinated globally and better reported. Standard ways of reporting on FEWS investments as well as on the benefits, including avoided losses, of FEWS need to be developed.
- An international hub should be established to monitor the status of FEWS in collaboration with national FCCs. Such hub might logically be hosted by WMO. Such a hub may support sharing of FEWS-related information for research and further development of FEWS and contribute to monitoring progress of the DRR-related global development agenda.
- An index-based evaluation system to rank FEWS according to their effectiveness in flood disaster mitigation needs to be developed. Such a ranking system will consider a range of technical and non-technical aspects of FEWS, and will provide standards for FEWS development, a clear roadmap for improving FEWS effectiveness and an incentive for FEWS improvement in the context of achieving global DRR agenda.
- Integration between technical (risk knowledge, monitoring and forecasting components) and non-technical (warning dissemination, communication and response capabilities) components of FEWS i.e., between institutions responsible for flood forecasting and agencies responsible for issuing, communicating warnings, community preparedness and awareness needs to be continuously strengthened.
- Enhanced community support to FEWS needs to be ensured by including social awareness programs, regular post-disaster feedback surveys from target communities and provision of community-tailored response and evacuation plans.

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REFERENCES

Adams, T., & Pagano, T. (2016). Flood Forecasting: A Global Perspective. 10.1016/B978-0-12-801884-2.09999-0.

Alberta WaterSMART. (2014). Flood Forecasting Jurisdictional Review. Retrieved from https://albertawater.com/docs-work/projects-and-research/114-flood-forecasting-jurisdictional-review/file

Arias, J. K. B., Dorado, R. A., Mendoza, M. E. T., & Ballaran, V. G. (2015). Exploring the Potentials of a Technology-Based Flood Early Warning System in Laguna, Philippines: A Cost-Benefit Analysis. *In Cost-Benefit Studies of Natural Resource Management in Southeast Asia* (pp. 369–387). DOI: 10.1007/978-981-287-393-4_17

BoM - Bureau of Meteorology, Australian Government. (2018) - National Arrangements for Flood Forecasting and Warning. Retrieved from http://www.bom.gov.au/water/floods/document/National_Arrangements_V4.pdf

Cools, J., Innocenti, D., & O'Brien, S. (2016). Lessons from flood early warning systems. *Environmental Science & Policy*, 58, 117–122. DOI: 10.1016/j.envsci.2016.01.006

CREWS - Climate Risk and Early Warning Systems. (2017). Annual Report (No 1). Retrieved from https://ane4bf-datap1.s3-eu-west-1.amazonaws.com/wmocrews/s3fs-public/ckeditor/files/CREWS_AR_2017_20180420_EN_with_links_interactive_0.pdf

Dutta, R., Basnayake, S., & Ahmed, A. K. (2015). Assessing Gaps in Strengthening Early Warning System in Managing Disasters in Cambodia. *IDRiM Journal*, 5(2), 167–175, DOI: 10.5595/idrim.2015.0104

Environment Agency. (2009). UK Coastal Monitoring and Forecasting (UKCMF): 2009 to 2019 strategy. Retrieved from: https://www.gov.uk/government/publications/uk-coastal-monitoring-and-forecasting-ukcmf-2009-to-2019-strategy

Faisal, I.M, Kabir, M.R, & Nishat, A. (1999). Non-structural flood mitigation measures for Dhaka City. *Urban Water*, 1(2), 145–153. https://doi.org/10.1016/S1462-0758(00)00004-2

GSMA - Global System for Mobile Communications Association. (2015). Disaster Response DEWN - Dialogs' Disaster and Emergency Warning Network. Retrieved from: https://www.gsma.com/mobilefordevelopment/wp-content/uploads/2015/02/GSMA_Dialog_DEWN_Disaster_Emergency_Warning_Network.pdf

Hallegatte, S. (2012). A cost-effective solution to reduce disaster losses in developing countries and evacuation: Hydro-meteorological services. Early Warning, and Evacuation. Retrieved from http://documents.worldbank.org/curated/en/190261468181486694/pdf/WPS6058.pdf

Holland, P. (2008). Fiji Technical Report - An economic analysis of flood warning in Navua, Fiji EU EDF 8-SOPAC Project Report. Retrieved from http://www.socialvalueuk.org/report/fiji-technical-report-an-economic-analysis-of-flood-warning-in-navua-fiji/

Iglesias, G.R. (2015). Flood early warning systems as a climate resilience measure in Indonesia, Asian Disaster Management News, 21.

Liu, C., Guo, L., Ye, L., Zhang, S., Zhao, Y., & Song, T. (2018). A review of advances in China's flash flood early-warning system. *Natural Hazards*, 92(2), 619–634. https://doi.org/10.1007/s11069-018-3173-7

Markert, K. N., Chishtie, F., Anderson, E. R., Saah, D., & Griffin, R. E. (2018). On the merging of optical and SAR satellite imagery for surface water mapping applications. *Results in Physics*, 9, 275-277. https://doi.org/10.1016/j.rinp.2018.02.054

Pappenberger, F., Cloke, H., Parker, D., Watterhall, F., Richardson, D., & Thielen, J. (2015). The monetary benefit of early flood warnings in Europe. *Environmental Science & Policy*, 51, 278–291. http://dx.doi.org/10.1016/j.envsci.2015.04.016

Saravi, S., Kalawsky, R., Joannou, D., Rivas-Casado, M., Fu, G., & Meng, F. (2019). Use of artificial intelligence to improve resilience and preparedness against adverse flood events. *Water*, 11(5), 973-986. https://doi.org/10.3390/w11050973

Smith, P. J., Brown, S., & Dugar, S. (2017). Community-based early warning systems for flood risk mitigation in Nepal. *Natural Hazards and Earth System Sciences*, 17(3), 423–437, https://doi.org/10.5194/nhess-17-423-2017

Soille, P., Burger, A., Rodriguez, D., Syrris, V., & Vasilev, V. (2016, March). Towards a JRC earth observation data and processing platform. In Proceedings of the Conference on Big Data from Space (BiDS'16), Santa Cruz de Tenerife (pp. 15-17), http://dx.doi.org/10.2788/854791

Sparks, D. (2012). Aid investments in disaster risk reduction - rhetoric to action. Retrieved from http://devinit.org/post/aid-investments-in-disaster-risk-reduction-rhetoric-to-action/

Subbiah, A. R., Lolita, B., & Ramraj, N. (2008). Background Paper on Assessment of the Economics of Early Warning Systems for Disaster Risk Reduction World Bank Group for Disaster Reduction and recovery. Retrieved from https://econadapt-library.eu/node/1546

Thielen-del Pozo, J., Thiemig, V., Pappenberger F., Revilla-Romero, B., Salamon, P., De Groeve, T., & Hirpa, F. (2015). The benefit of continental flood early warning systems to reduce the impact of flood disasters. EUR 27533 EN. DOI: 10.2788/46941

Thorndahl, S., Einfalt, T., Willems, P., Nielsen, J. E., ten Veldhuis,M.-C., Arnbjerg-Nielsen, K., Rasmussen, M. R., and Molnar, P.: (2017). Weather radar rainfall data in urban hydrology, *Hydrology and Earth System Sciences*, 21, 1359–1380, https://doi.org/10.5194/hess-21-1359-2017.

Tondapu, G., Markert, K., Lindquist, E. J., Wiell, D., Díaz, A. S. P., Johnson, G., ... & Patterson, M. S. (2018, December). A SERVIR FAO Open Source Partnership: Co-development of Open Source Web Technologies using Earth Observation for Land Cover Mapping. In AGU Fall Meeting Abstracts.

United Nations. (2000). Millennium Declaration. Retrieved from http://www.un.org/millennium/declaration/ares552e.htm

United Nations. (2018). SDG 11 Synthesis report: Tracking Progress towards Inclusive, Safe, Resilient and Sustainable Cities and Human Settlements, Nairobi, Kenya. Retrieved from http://uis.unesco.org/sites/default/files/documents/sdg11-synthesis-report-2018-en.pdf

UNDRR- United Nations Office for Disaster Risk Reduction. (2004). Early Warning as a Matter of Policy. Retrieved from https://www.UNDRR.org/files/8290_earlywarningasamatterofpolicy.pdf

UNDRR- United Nations Office for Disaster Risk Reduction. (2005). Hyogo Framework for Action. Retrieved from https://www.UNDRR.org/files/1037_hyogoframeworkforactionenglish.pdf

UNDRR- United Nations Office for Disaster Risk Reduction. (2006). Global Survey of Early Warning Systems: An Assessment of Capacities, Gaps and Opportunities towards Building a Comprehensive Global Early Warning System for all Natural Hazards. Retrieved from https://www.UNDRR.org/2006/ppew/info-resources/ewc3/Global-Survey-of-Early-Warning-Systems.pdf

UNDRR - United Nations Office for Disaster Risk Reduction. (2015). Sendai Framework for Disaster Risk Reduction 2015-2030, p.32, Retrieved from https://www.unisdr.org/files/43291_sendaiframeworkfordrren.pdf

UNISDR - United Nations Office for Disaster Risk Reduction. (2017). "Report of the Open-Ended Intergovernmental Expert Working Group on Indicators and Terminology Relating to Disaster Risk Reduction, United Nations General Assembly. Agenda Item: 19 (C)." https://www.preventionweb.net/files/50683_oiewgreportenglish.pdf

Wallemacq, P., & House, R. (2018). Economic losses, poverty & disasters: 1998-2017. Center for Research on the Epidemiology of Disasters, United Nations International Strategy for Disaster Reduction, Retrieved from: https://www.UNDRR.org/we/inform/publications/61119

WMO- World Meteorological Organization. (2011). Manual on Flood Forecasting and Warning. Retrieved from http://www.wmo.int/pages/prog/hwrp/publications/flood_forecasting_warning/WMO%201072_en.pdf

WMO- World Meteorological Organization. (2013). Integrated flood management tools series: Flood Forecasting and Early Warning. Retrieved from https://library.wmo.int/doc_num.php?explnum_id=4269

Yu, W., Nakakita, E., Kim, S., Yamaguchi, K., 2018. Assessment of ensemble flood forecasting with numerical weather prediction by considering spatial shift of rainfall fields. KSCE J. Civ. Eng. 1–11. http://dx.doi.org/10.1007/s12205-018-0407-x.

Zahmatkesh, Z., Jha, S.K., Coulibaly, P., (2019), An overview of river flood forecasting procedures in Canadian watersheds, Canadian W*ater Resources Journal / Revue canadienne des ressources hydriques*, 44:3, 213-229, https://doi.org/10.1080/07011784.2019.1601598

ANNEX

Country	River Basins	Institution
Afghanistan	NA	The Ministry of Energy and Water of Afghanistan (MEW)
Bangladesh	Ganges, Brahmaputra, Meghna (GBM) and South-Eastern Hills	Bangladesh Water Development Board
Belize	Rivers in the West and South	Belize Met Service & Hydro Unit
Benin	Oueme, Niger, Mono, Couffo	Directorate General of Water (DGeau)
Benin, Burkina Faso, Cameroun, Côte d'Ivoire, Guinée, Mali, Niger, Nigeria, Chad	Niger River Basin	Niger Basin Authority (NBA)
Bhutan	Punatshangchu Basin (Puna-Wangdi Valley)	National Center for Hydrology and Meteorology
Burkina Faso	Volta River Basin	Service Hydrologique
Cambodia	Mekong River Basin	Mekong River Commission Secretariat
Cambodia, Loa, Thailand, and Vietnam	Lower Mekong Basin	The Mekong River Commission (MRC)
Canada	Multiples	The Ministry of Sustainable Development, Environment, and Fight Against Climate Change (MD-DELCC) Government of Quebec
Canada	Great Lakes Basin, Nelson River basin, Ottawa River basin and James and Hudson Bay Basin,	Ministry of Natural Resources and Forestry
Canada	(all watersheds), Fraser, Thompson, Skeena, Columbia, others	Provincial Government (British Columbia)
Canada	Peace Basin; Athabasca Basin; North Saskatchewan River Basin; Red Deer River Basin; Bow River Basin; Oldman River Basin; South Saskatchewan River Basin	Government of Alberta
El Salvador	Rio Grande de San Miguel	Ministry of Environment and Natural Resources of El Salvador
Ethiopia	Awash River Basin Authority	National Meteorology Agency of Ethiopia (NMA), Disaster Risk Management Council (DRMC), Awash River Basin Authority (AWRBA)
France	NA	Central Service of Hydrometeorology and Support to Flood Forecasting (SCHAPI)
Germany	Rhine, Moselle	Landesamt für Umwelt Rheinland-Pfalz
Greece	NA	NA
Guinea	Niger and Senegal River	NA
Honduras	Choluteca	Centro Nacional de Estudios Atmosféricos, Oceanográficos y Sísmicos (CENAOS)
I.R of IRAN	Karoon, Karkhe, Dez in south-west Iran and in internal small basins for flash flooding in central and north of IRAN	Iran Meteorological Organization (IRIMO), Ministry of Energy and Water management, national Emergency and Rescue Management
India	Ganga	India Metrological Department

Country	River Basins	Institution
Japan	Arakawa (Kanto Region)	The Ministry of Land, Infrastructure, Transport and Tourism (MLIT), Japan
Madagascar	Fiherenana	Direction Générale de la Météorologie
Malaysia	Kemaman	National Hydraulic Research Institute of Malaysia (NAHRIM)
Mongolia	Tuul River basin	National Agency for Meteorology and Environment Monitoring, Tuul River Basin Administration, National Emergency Management Agency of Mongolia
Myanmar	Ayeyarwady	Department of Meteorology and Hydrology
Myanmar	Ayeyarwady, Chindwin, Sittoung, Bago, Dokehtawady, Shwegyin, Ngawun, Thanlwin, Myittha, Toe, Kalaten, Laymyo	Department of Meteorology and Hydrology, Ministry of Transport and Communications
Namibia	Zambei, Cuvelai,Cuando Cubango,Kunene and Orange	Ministry of Agriculture Water and Forestry
Nepal and India	Ratu , Koshi	International Centre for Integrated Mountain Development (ICIMOD)
Nepal	Imja Khola, Dudhkoshi, Kankai, Koshi, Gandaki, Karnali, Rapti,Babai,Narayani,Bagmati, West Rapti, Babai (southern parts of Nepal)	Department of Hydrology and Meteorology (DHM), Nepal
Nigeria	NA	Federal Ministry of Environment
Peru	RIMAC	Servicio Nacional De Meteorological E Hidrologia Del Peru
Philippines	Pampanga River Basin	The Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA)
Russian Federation	Amur	Municipal Housing Maintenance Companies Russian Federation (HMC RF)
Slovakia	Danube and Viszla basins	Slovak Hydrometeorological Institute
South Korea	Han River (Hangang River)	Han River Flood Control Office, Ministry of Land, Infrastructure and Transport
Sri Lanka	Kalu River basin	Irrigation Department
Sudan	Blue Nile River, Tekezi/Atbara River and Main River Nile	Ministry of Water Resources, Irrigation and Electricity
Taiwan	Tamsui River	National Taiwan University
Trinidad	Caroni River	Water Resources Agency
Turkey	Flash Flood EWS	Turkish State Meteorological Service
Ukraine	Prut Siret	Ukrainian Hydrometeorological Center
Viet Nam	Mekong River Basin	Delft - FEWS and Regional Flood Management and Mitigation Centre

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