Flood Risk Modeling to Support Risk Transfer:

Challenges and opportunities in data-scarce contexts

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Abbreviations

ADB	Asian Development Bank
ARC	African Risk Capacity Limited
CAPRA	The CAPRA Probabilistic Risk Assessment Platform
CAREC	Central Asia Regional Economic Cooperation
CCRIF	Caribbean Catastrophe Risk Insurance Facility
CHIRPS	Climate Hazards Group InfraRed Precipitation with Stations
CIMA	The International Center for Environmental Monitoring - CIMA Research Foundation
CNN	Convolutional Neural Network
DEM	Digital Elevation Model
DRFI	Disaster Risk Financing & Insurance
DRM	Disaster Risk Management
DRR	Disaster Risk Reduction
DTM	Digital Terrain Models
EMDE	Emerging Market Developing Economies
EO	Earth Observation
EP	Exceedance Probability
FLOPROS	Global Database of Flood Protection Standards
FRM	Flood Risk Management
GDP	Gross Domestic Product
GEM	The Global Earthquake Model Foundation
GPD	Gridded Precipitation Datasets
GPM	Global Precipitation Measurement
GRMA	Global Risk Modelling Alliance
GSMaP	Global Satellite Mapping of Precipitation
HAND	Height Above Nearest Drainage
IDF	Insurance Development Forum
JBA	JBA Risk Management / JBA Consulting
LiDAR	Light Detecting and Ranging
MODIS	Moderate Resolution Imaging Spectroradiometer
NRT	Near Real-Time
ODI	Overseas Development Institute
PDNA	Post-Disaster Needs Assessment
RCP	Representative Concentration Pathway
SEADRIF	Southeast Asia Disaster Risk Insurance Facility
SoP	Standards of Protection
SRTM	Shuttle Radar Topography Mission
SWE	Shallow Water Equations
TAMSAT	Tropical Applications of Meteorology Using Satellite
TRMM	Tropical Rainfall Measuring Mission
UNGRD	Unidad Nacional para la Gestión del Riesgo de Desastres (National Unit for the Management of Disaster Risk), Colombia
WTW	Willis Towers Watson

Executive Summary

Flooding is one of the most frequent and severe hazards affecting people and the built environment. Increasing rainfall intensity due to climate change, population growth and urbanization are expected to significantly increase flood risk in the coming decades, leading to greater economic losses and disruption to communities. This risk can be reduced or even prevented through the implementation of flood risk management (FRM) strategies.

A comprehensive approach to FRM incorporates multiple components including risk identification, risk reduction, preparedness, financial protection and resilient recovery. Financial protection through the application of Disaster Risk Financing & Insurance (DRFI) instruments complements, but does not replace, the need for Disaster Risk Management (DRM) and Disaster Risk Reduction (DRR) measures. Financial protection should be applied to transfer the residual risk that can't be reduced or managed through other components.

Assuming flood risk reduction and flood risk management strategies have been fully implemented, risk financing approaches can be identified to ensure financial protection is in place before events occur. Insurance provides one risk financing mechanism for enabling greater financial resilience in Emerging Market Developing Economies (EMDEs), however, there is a scarcity of data to support risk assessment for floods, and subsequently a lack of solutions available to countries.

There are multiple challenges to developing flood risk models that are acceptable to both the country seeking financial protection and the reinsurance industry. Flood is a complicated peril to model due to its highly localized nature and the detailed input data required to reduce uncertainty to an acceptable level. This data, whether it be related to hazard, exposure or vulnerability, is of critical importance for the modeling and in EMDE's it is often not available or not of sufficient quality. In addition, this lack of data reduces the ability to demonstrate the model's accuracy through whole-model validation. However, with the increasing availability of global, regional and sectoral data and the constantly improving techniques for risk modeling and monitoring, it is possible to successfully develop flood models to support the placement of risk transfer instruments at risk-informed premiums.

This report reviews the processes and challenges in developing flood risk models to support disaster risk financing and insurance and proposes guidelines for risk modeling and risk monitoring in support of flood risk transfer instruments for data-scarce contexts. The guidance in this report is informed by consultations with insurance industry and development sector practitioners including with flood hazard and risk modeling experts, underwriters and brokers, and earth observation specialists. The guidance should be considered by organizations commissioning flood models for DRFI purposes, to develop greater understanding of the technical and non-technical needs of such projects.

Photo credit: Wutthichai / Shutterstock.com

1. Introduction

Globally more than 2 billion people live in areas that are expected to be inundated by a 1-in-100-year flood event, whilst 89 percent of the 1.47 billion people exposed to the risk of intense floods live in low- and middle- income countries (Rentschler and Salhab 2020). Individual flood events can impact a large area and lead to significant amounts of damage, having caused over US$650 billion of economic loss between 1998 and 2017 (Wallemacq and House 2018). These high losses come from the severe impact to urban areas, as settlements are often built beside rivers, along with large impacts to agriculture and food security.

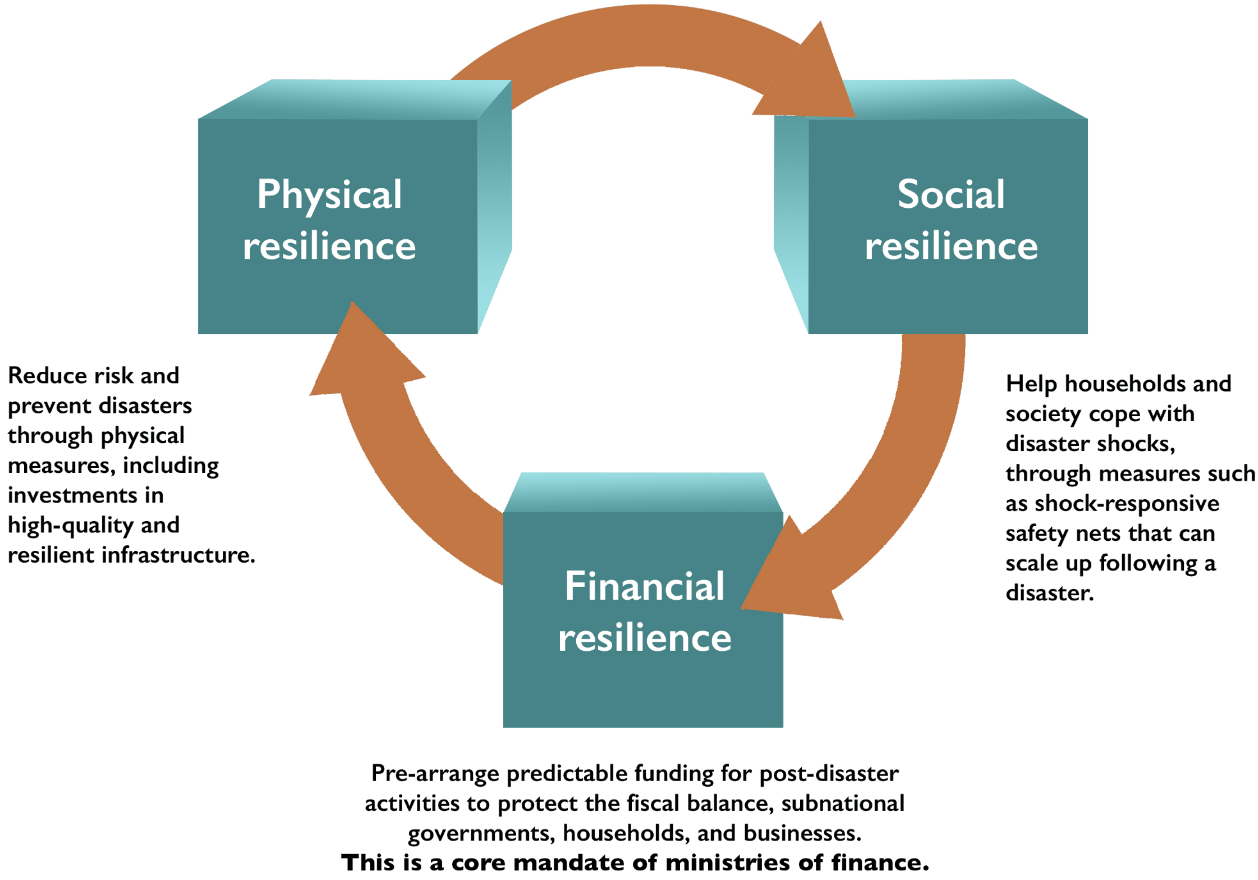
Climate change is expected to increase the intensity of rainfall events and an increase in heavy rainfall linked to climate change has already been observed globally (Met Office 2022). This increase in rainfall intensity is expected to significantly increase pluvial (surface water) flood risk, particularly in urban areas, whilst also affecting fluvial (river) flood risk. Meanwhile, population growth and urbanization are increasing the concentration of assets in vulnerable locations, and this is also expected to contribute to increasing losses (Tellman 2021).

Frequent flooding can cause sufficient disruption to health, livelihoods and economies that it often hinders local development and growth. Meanwhile major disasters can cause significant and sudden reduction in economic activity and GDP (Gross Domestic Product), affecting long-term growth and economic development of countries, forcing more people into poverty. These effects can be addressed through Flood Risk Management (FRM) strategies that combine Disaster Risk Management (DRM), including Disaster Risk Reduction (DRR), and Disaster Risk Financing & Insurance (DRFI). DRM and DRR aim to prevent new and reduce existing disaster risk through reducing and managing conditions of hazard, exposure and vulnerability (e.g., through engineered flood protection) whilst DRFI aims to increase the financial resilience of all stakeholders through the ex-ante funding or transfer of residual risk.

FRM strategies are becoming more common in low- and middle-income countries as a way to build social, physical and financial resilience to disasters (Figure 1). This is in part due to the increasing availability of analytics used to identify the risk and potential impacts from flooding. However, whilst these analytics are used to support decisions around whether to manage or reduce risk, DRFI, and in particular risk transfer, is frequently considered less often. In some cases, this can be due to a lack of understanding of risk transfer and its potential value but can also occur due to an absence of sufficiently robust risk analytics. A robust financial resilience strategy must be underpinned by a good understanding of risk from appropriate risk data and analytics (World Bank 2019) and the requirements for this are often more particular than those used to support greater physical and social resilience.

Figure 1: Three elements of disaster resilience.[1]

Source: World Bank



Financial resilience involves pre-arranging predictable funding to address any residual that cannot be reduced through DRM and DRR. Ex-ante financial instruments include reserve funds, contingent budget lines, contingent credit, and market-based risk transfer solutions such as insurance and catastrophe bonds. Whilst flood insurance plays an important role in reducing the financial impacts of flood events on households, businesses and the government, even in high-income countries the prevalence of flood insurance is highly variable. This is due to the high granularity of data required and the uncertainty in the model results compared with other natural hazards.

The purpose of this report is to provide guidance for development professionals on the key aspects for developing flood risk models to support Disaster Risk Financing & Insurance (DRFI) solutions, particularly in data-scarce contexts, and for insurance industry practitioners on the different requirements when developing models in EMDEs. The report focusses solely on fluvial and pluvial flooding due to their interdependencies and similar modeling approaches and assumes that DRR and DRM approaches have been implemented and that as part of the longer-term management of the residual risk DRFI and risk transfer are required.

This report reviews the processes and challenges in developing models to support the placement of either indemnity, payment based on loss experience, or parametric, payment based on a pre-defined set of event parameters, solutions. Due to its advantages in data- and capacity-limited areas parametric insurance is given greater emphasis across the report.

[1] World Bank Technical Contribution to the 2019 G20 Finance Ministers' and Central Bank Governors' Meeting - Boosting Financial Resilience to Disaster Shocks: Good Practices and New Frontiers

2. Flood catastrophe modeling to support risk-informed decision making

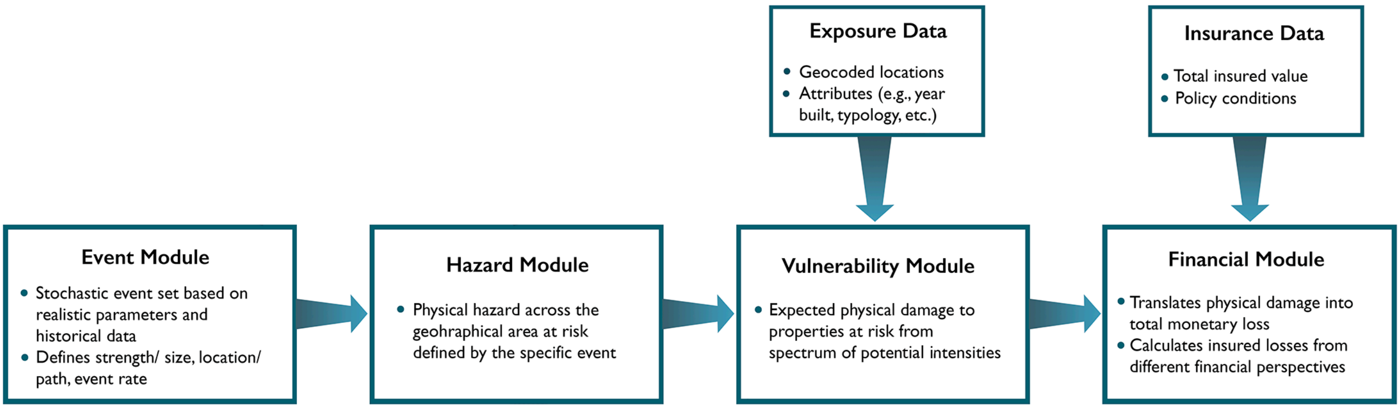
Catastrophe risk models have been used by the finance industry for over 30 years to evaluate and manage catastrophe risk from natural and non-natural perils. Flood risk modeling provides a methodology for all interested parties (e.g., insurers, reinsurers and cedants, including governments) to better understand the potential impact from floods by quantifying the risk in terms of monetary losses or affected people. This supports the development of effective FRM strategies, in particular DRFI strategies that include a risk layering approach to provide sufficient financial liquidity through pre-determined financial instruments for rapid and effective post-disaster response. Models underpin risk-informed decision-making as part of FRM strategies by enabling:

- The estimation of risk, and creation of disaster risk profiles to analyze losses on an annual average basis and due to extreme events, using simulated event sets that provide a better picture of those extreme events not well represented in the historical record alone.
- Cost-benefit analyses of various DRR and adaptation options, including investments in structural protection and nature-based solutions.
- The pricing of flood risk, to determine a suitable instrument, structure and insurance premium for risk transfer products.

Flood risk modeling was not possible before computing power increased, approximately 15-20 years ago, when it became possible to model flood dynamics at country-wide scales. This improvement in technology together with the release of government Digital Terrain Models (DTM) and Light Detecting and Ranging (LiDAR) data has been the driver for the greater amount of flood models available, and models now cover the main types of flooding described in Box 1.

Figure 2: Schematic of the catastrophe modeling process.

Source: Author's own



There are four core modules in a catastrophe risk model (Figure 2). These are: (i) an event module, which characterizes the frequency and severity of many thousands of plausible simulated events; (ii) a hazard module, which determines the hazard intensity (e.g., inundation depth) associated with each event; (iii) the vulnerability module, which relates the hazard intensity to expected physical damage to assets or impact on population; and (iv) the financial module, which converts the expected damage into a financial loss estimate, accounting for insurance policy conditions where relevant. In addition to these four modules there are two data inputs: (i) exposure data, which describes the distribution and characteristics of population and assets; (ii) insurance data providing policy terms and conditions in DRFI contexts. Extensive description of risk assessment processes are provided by GFDRR (2014) and the development and application of catastrophe models is provided in Mitchell-Wallace, et al. (2017) and Michel (2018).

During the modeling process a catastrophe risk model needs to account for both aleatory uncertainty (variation in outcome due to inherent randomness) and epistemic uncertainty (variation in outcome due to a lack of knowledge) to provide not only an estimation of risk but also the range of possible losses around this estimate. The uncertainty needs to be captured across all modules and data inputs and is likely to be greater in data poor contexts due to the lack of accurate data.

Proprietary flood risk models have dominated the insurance industry for many years because they have become a standard within the industry and are backed by specialist development and client support teams. However, the development of these models has been prioritized in countries with well-established insurance markets, to ensure a return on investment. Models are increasingly being developed for regions with less mature insurance markets, but these tend to be global models, in-house models not made widely available, or country-specific models developed by consultants as part of development sector projects, which are often not made available on an ongoing basis. As a result, there remain many countries for which there are no models in active use by the industry.

Open flood risk models offer opportunities for the insurance industry and local experts to collaborate on flood modeling (Box 2). This can result in improved models and risk information and contribute significantly to improving risk analytics capacity in low- and middle-income countries, where barriers to accessing risk information hinder risk-informed decision-making (Insurance Development Forum 2020). Open risk modeling can also enable in-country experts to own and maintain their own views of risk through improved usability, transparency and choice of models and data, and greater ability to compare and interrogate risk insights (International Climate Initiative 2020). In data-scarce contexts the greater transparency of assumptions and limitations, and greater potential for users to test and adjust model components can contribute to an improved understanding of flood modeling for DRFI.

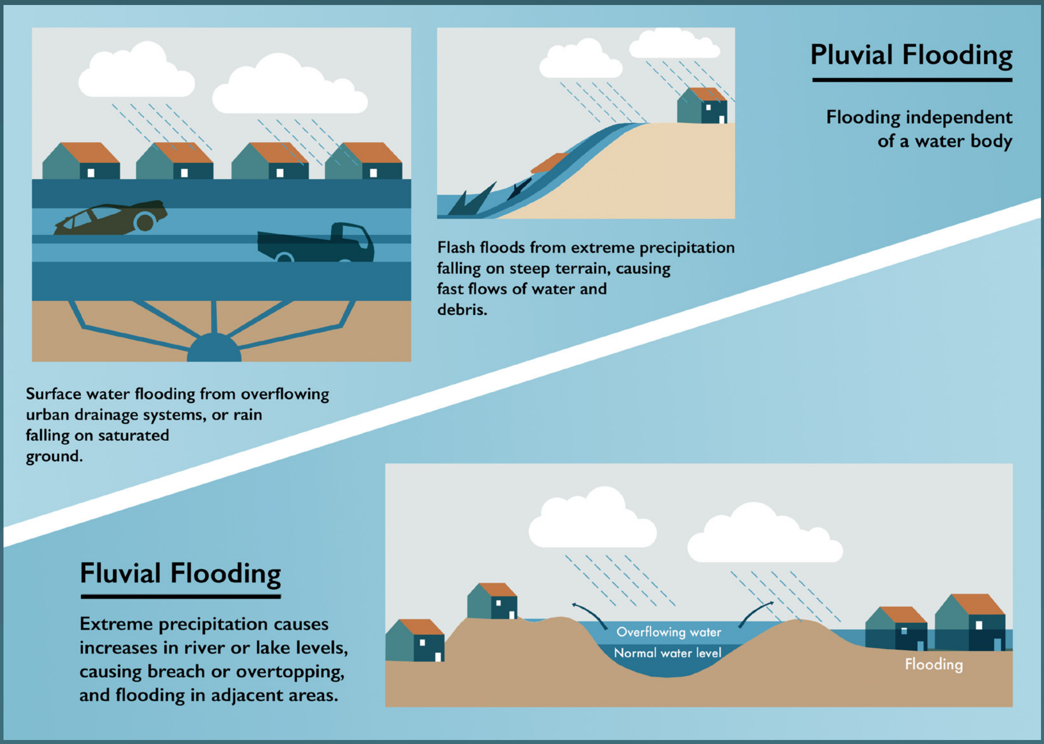
The following sections will focus more on the processes and data that should be included in each component for a model to support DRFI applications, and the challenges in achieving this level of analytics for data-scarce contexts.

Box 1: Types of Flood Risk

Flooding is most often classified as fluvial, pluvial, or coastal, although there are other sources of inundation including groundwater flooding, dam breach, tsunami, spring-melt and glacial lake outburst floods.

Figure 3: Schematic showing pluvial and fluvial flood mechanisms.

Source: Author's own



Fluvial or river flooding happens when the volume of water in a river channel exceeds the carrying capacity of that channel, causing it to breach defenses or overtop its banks. The severity of a fluvial flood event is determined by the occurrence of a peak flow in the channel. This is influenced by rainfall volume and intensity, but also the timing and duration of precipitation over different parts of the catchment, the confluence of multiple river channels, occurrence of seasonal snowmelt, and storage of excess flow (e.g., dams, reservoirs or storage on the floodplain). Particular antecedent ground conditions (e.g., hard ground due to drought, or saturated due to long wet periods), artificial drainage systems and unvegetated or less permeable surfaces generally speed up the run-off of water into river channels. This contributes to higher flood peaks, compared to conditions when water is able to infiltrate more slowly through the catchment reaching the river more gradually, reducing the peak flow.

Pluvial flooding includes surface water flooding, flash flooding, and storm runoff, all of which occur due to high-intensity rainfall events that exceed the drainage capacity of the ground or drainage systems, resulting in flooding on the surface. In pluvial flooding water can 'pond' in small depressions in the ground or cause a torrent of water flowing across the ground, depending on the slope gradient and other factors. Usually, pluvial flood events have a short duration and affect only a localized area.

These two types of flooding can occur independently, but flood events often consist of both fluvial and pluvial flooding. It can be challenging to determine which type of flood is responsible for the event losses and to differentiate between the impacts from these types of flooding compared to coastal flooding, storm surge and or ingress of water due to wind damage.

Box 2: Open risk modeling

The Insurance Development Forum (IDF) Risk Modelling Steering Group advocates for and employs open risk modeling in their goals to democratize risk information and increase risk analytics capacity to enable greater financial resilience (Insurance Development Forum 2020).

An open risk model is a model which is available for anyone to re-use. They can be considered a digital public good – a good or service in digital form that anyone may access or benefit from without excluding or diminishing its benefit to others (UNDRR and GFDRR 2022). The Oasis Loss Modelling Framework, OpenQuake, Climada, CAPRA and RiskScape are all examples of open-source risk modeling platforms in which risk models can be built and run. Open risk models can be more easily interrogated to understand their approaches and assumptions, and more readily compared to other models.

Some models use open-source software which allows anyone to use, study, change and distribute it. Open model documentation should be available on the internet free of charge and without barriers to access or re-use. Open models should use and produce processes and data that adhere to open standards – established requirements or definitions that are made openly available and are developed through a collaborative and a consensus-driven process.

2.1 Requirements and challenges in the event and hazard modules

Together, the event and hazard modules describe the frequency and severity of potential flood events. The event module comprises a stochastic event set – a catalogue of simulated plausible events based on realistic parameters and historical events. A stochastic event set provides a more complete view of possible events than the historical record, which is typically too short in duration and contains incomplete information to be a reliable guide to extreme risk. Key characteristics are described for each event: location, severity or intensity, and rate or frequency of occurrence. The hazard module describes the distribution of hazard intensity, typically flood depth, on and off the floodplain for individual events and representative return period events (e.g., 1-in-10 or 1-in-100-year return period) contained in the stochastic event set. This is used as the basis for estimating the impacts of each event, which are later combined to generate an exceedance probability curve and loss statistics. The following sections describe the processes that are applied to determine hazard for both fluvial and pluvial flooding along with the challenges of implementing these modeling techniques to support the design of DRFI solutions.

2.1.1 Fluvial flood modeling approaches

Several approaches can be used to model fluvial flood hazard, with the input data requirements varying depending on the approach (Figure 4). Models typically account for the intensity, duration and spatial distribution of precipitation, catchment characteristics (terrain, geology and landcover), antecedent conditions (i.e., soil saturation), river levels, temperature to capture levels of evapotranspiration and historical discharge data.

Typically, hydraulic models within catastrophe models are used to estimate the distribution of flood intensity, although Earth Observation (EO) data can also be used to characterize this. Hydraulic models use the volume of water flowing through the channel ('discharge') as an input, in the form of hydrographs describing the timing and peak volume of extreme flows. The hydraulic model simulates the flow of discharge through the river network, including the influence of channel dimensions and roughness, or flow controls. Where flow volumes exceed the channel capacity, the model simulates how much water will flow over the floodplain and where this occurs.

A preceding step is required to generate the hydrographs, and this can be done in one of two main ways. The first uses a statistical model to extrapolate extreme discharge or streamflow values from the historical flow gauge data set; this approach requires records of historical water levels and discharge to have been recorded using gauges over a significant period of time, generally at least 30 years. If this data exists, the probability distribution for discharge can be *directly* calculated from the river gauge data to identify potential frequent and extreme events. The benefit of this approach is that it provides the most accurate representation of both regular and extreme events. However, it relies on good availability and quality of flow gauge data and as this is often lacking in developing countries, alternative methods need to be used.

The second approach is to use rainfall-runoff models, which incorporate hydrological modeling to estimate flow from meteorological data (namely precipitation and temperature), and catchment data on elevation, soil type and land use. The hydrological model estimates the accumulation of rainfall falling at any location in the model domain and routes that water to the river catchment with the timing and volume of water reaching the river network dependent on evapotranspiration rates, overland flow and infiltration rates amongst other factors. This approach relies on computerized representations of watersheds, which are often simplified and don't reflect reality, including human influence, which can impact rainfall-runoff relationships significantly and introduce greater uncertainty into the model. However, the advantage of this approach is that antecedent conditions can be better represented than when using discharge data and it requires datasets that are often more available in data-scarce regions.

For this second approach, there are two methods depending on availability of rainfall and discharge data. Where there are good historical records, these can be used directly in a rainfall-runoff model with a stochastic streamflow model used to simulate streamflow events with different annual frequencies. Where data is lacking, Gridded Precipitation Datasets (GPDs) can be used to simulate tens or hundreds of thousands of plausible precipitation events, which are used to estimate the river discharge associated with different annual frequency of precipitation.

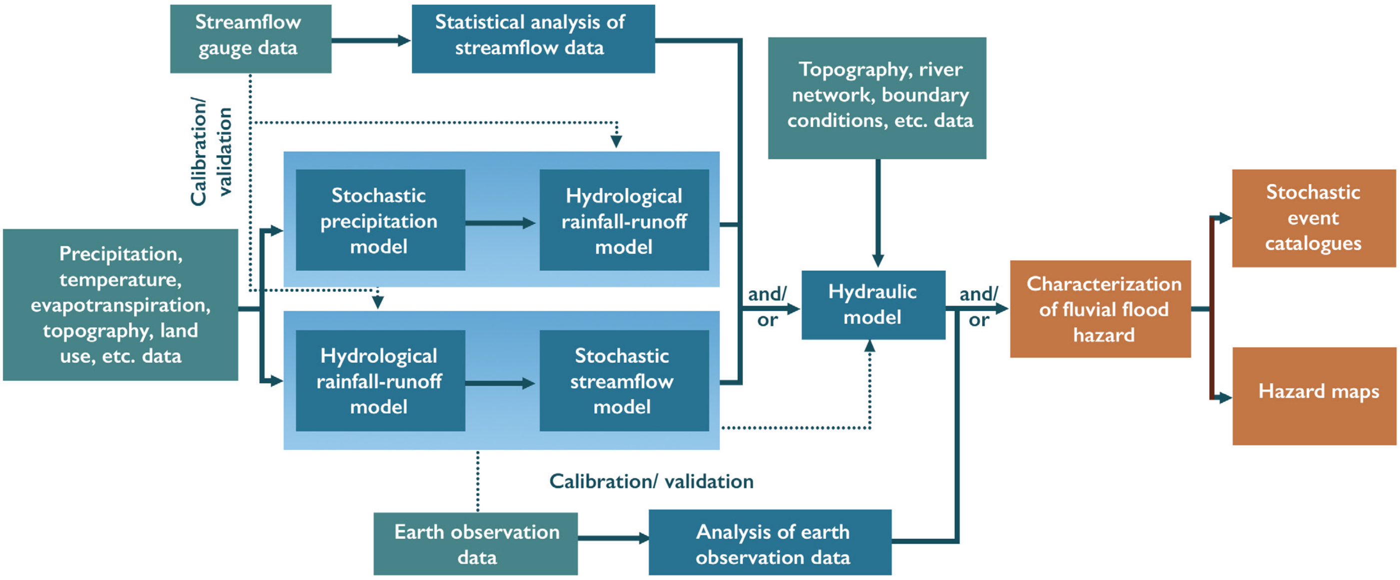
The overall choice of approach used is determined by data availability and data quality, the technical expertise available to work with the datasets as well as the risk transfer requirements of an application. An example modeling approach is outlined in Box 3.

Once extreme discharge estimates have been calculated correlation matrices need to be developed to ensure the stochastic event set follows the same statistical properties as the historical time series. This includes correlation between the annual maxima across all causal mechanisms and locations (e.g., two floods of the same type at two nearby locations are strongly correlated whereas floods of different types and at distant locations are much less correlated) and that the probability of these annual maxima within one event and across multiple events agrees with the historical time series.

Figure 4: Example approaches to characterize fluvial flood hazard.

The key inputs are shown in green, model components in blue, and outputs in orange. The dotted lines show other potential involvement of that box elsewhere in the process.

Source: Author's own



Box 3: Application of probabilistic modeling to risk analysis in support of disaster risk finance in the CAREC region.

The Central Asia Regional Economic Cooperation (CAREC) Program is a partnership of 11 countries that promotes growth and reduces poverty through collaboration. CAREC is being supported by funding from the Asian Development Bank (ADB) to identify opportunities to use disaster risk finance to transfer some of the financial impacts of severe flooding and earthquake to the financial sector. Critical to the design of risk transfer is a comprehensive analysis of natural hazard risk. A consortium of WTW, JBA, GEM and ODI collaborated on developing insight into economic and social impacts from hazard events and the creation of a user-friendly interface for presenting data to non-specialists.

JBA's probabilistic flood risk model is the first in the market to provide global coverage. For the CAREC project, this offered baseline flood modeling to which localized refinements were made. The hazard model includes two components; flood maps at 30m resolution and an extensive set of simulated flood events. Historic modeled rainfall data, known as reanalysis data, is the basis for both components: the event set uses advanced statistical techniques to create a much larger set of data that enables the risk from extreme events to be estimated, while the flood maps use the same reanalysis data, fed into complex hydrological and hydraulic models. The flexible framework within which the hazard component is embedded means that the exposure and vulnerability inputs could be easily updated to refine the outputs required within the project.

It is anticipated that refinement of the risk modeling and development of risk transfer options will take place in pilot countries, including holding local stakeholder discussions around availability of local data for validation of the model.

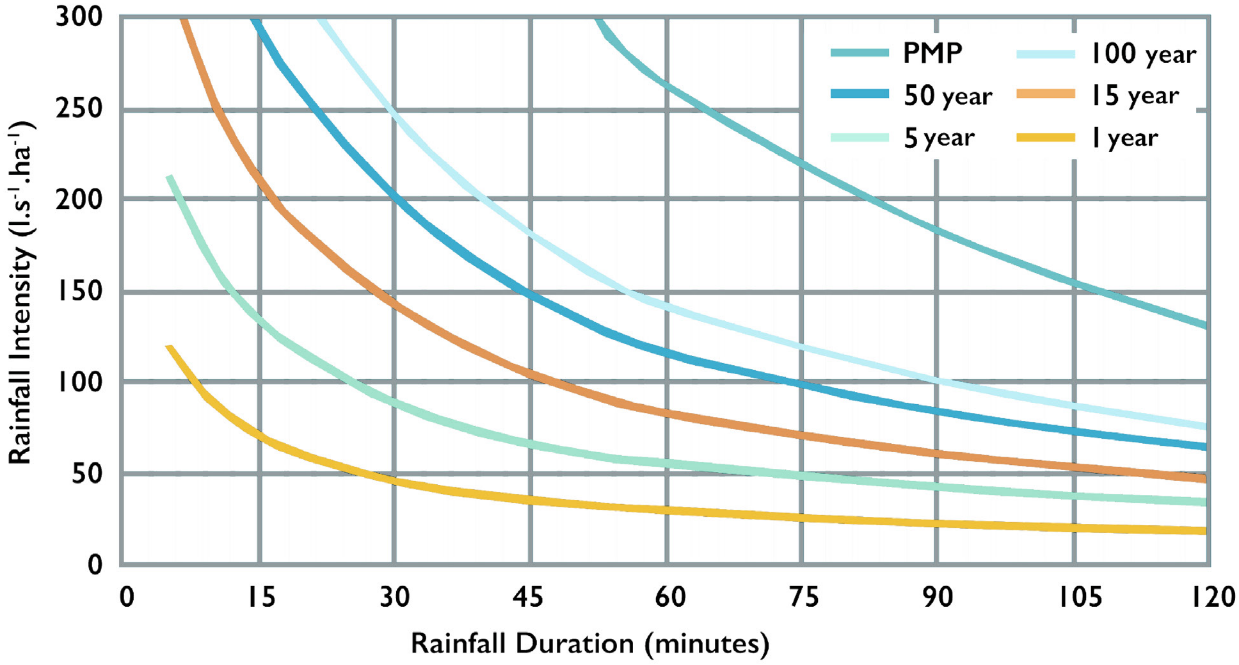
2.1.2 Pluvial flood modeling approaches

Pluvial flood modeling follows a similar approach to fluvial modeling but focusses on estimating the volume of water flowing into and collecting in depressions (low points) in the terrain. Typically, a dataset of maximum rainfall values is used to develop intensity-duration-frequency curves (Figure 5) which describes the amount of rainfall occurring in different duration events, with different annual frequencies. Small areas may be well represented by a single intensity-duration-frequency curve, whilst a large region may have many to reflect the variation in regional rainfall patterns. Precipitation values for selected return periods can be sampled from the intensity-duration-frequency curves and used as input into the hydraulic model. The hydraulic model then simulates evapo-transpiration, infiltration and overland flow of the volume of water, resulting in an estimate of the locations most likely to experience pluvial flooding with estimated flood depths for different return periods or annual frequencies.

Figure 5: Example intensity duration frequency curves.

Each curve describes the observed / expected relationship between rainfall intensity and duration, for rainfall events of different frequency in years return period, including Probable Maximum Precipitation (PMP).

Source: Image reproduced with permission of Impact Forecasting.



Two issues that complicate pluvial flood risk modeling are the scale of the modeling required and the topography of the land. When modeling pluvial flood risk at a large scale (e.g., multiple countries) it may be more realistic to apply alternative approaches where computing resource or sufficient supporting data are lacking. For example, assessing how prone an area is to surface flood based on the potential for floodwater to drain and pond there (flood susceptibility mapping) can be sufficient to characterize the hazard and exposure in high flood hazard areas, but lacks the quantification of potential damage. Pluvial flood modeling is also difficult in mountainous terrain where there are large changes in elevation over short distances. In these areas digital elevation models (DEMs) and digital terrain models (DTMs) are often of insufficient resolution to enable the pluvial flooding to be fully resolved and more detailed realizations of the topography are required (see Box 4).

2.1.3 Key challenges in fluvial and pluvial flood hazard modeling

There are many challenges in modeling flood hazard, including that the physical processes of flooding are highly localized, being characterized by significant spatial variability of rainfall, and highly (spatially and temporally) variable catchment and river channel conditions. Very significant differences in estimated losses can result from the different assumptions, processes and data on these points, with the most suitable modeling approach varying according to the specific information required for the end-use, the data available and computational demands. As for all perils, flood risk is highly dynamic, and can change through time due to many factors (GFDRR 2016).

Some of the key challenges associated with the key data inputs for flood modeling are:

- **Antecedent conditions** heavily influence the response of the river network, the floodplain and off-floodplain areas to extreme rainfall. In wet periods, channels can be close to capacity, and soils can be saturated leading to greater volumes of water flowing overland rather than infiltrating into the soil. Being able to assess the possibility of multiple events compounding the hazard is challenging but is a key element of the modeling approach. As the climate changes, changing seasonality and clustering of rainfall events may affect antecedent conditions, adding an additional influence on the likelihood and severity of flooding given intense rainfall events.

- **Rainfall data** limitations can be overcome by using Global Precipitation Datasets or climate reanalysis data which provide atmospheric parameters (temperature, pressure, wind) and surface parameters such as rainfall, soil moisture and sea-surface temperature. Estimates of rainfall from satellite data are less direct and less accurate than either gauges or radar, but can give consistent coverage, e.g., at 4km resolution, on a daily / sub-daily basis. These datasets are more widely available that discharge data and offer near-global coverage, however they can contain high levels of bias and often cannot capture localized rainfall intensity as well, due to the large grid cells, which is particularly needed to simulate flash flooding accurately.

  There are several data sets available – their inputs, methodologies and biases vary depending on region of interest and the dominant rainfall type (Maidment 2017) and decisions on which to use should be based on the intended application and target region. These include the Global Precipitation Measurement (GPM) mission (NASA n.d.) which builds on the earlier Tropical Rainfall Measuring Mission (TRMM). GPM is the origin of the Global Satellite Mapping of Precipitation (GSMaP) product, which provides global hourly rainfall intensity data at 0.1-degree resolution. Since 1981 the Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) provides 0.05-degree resolution data at up to daily resolution (Funk et al. 2014). Regional products can provide higher resolution data, such as the TAMSAT (0.0375-degree data since 1983 at 5-day intervals) (Maidment, Black, and Young 2017) and African Rainfall Climatology (ARC 2; 0.1-degree data since 1983 at minimum of 10-day intervals) (ICPAD n.d.)

- **Observations** (historical records) on precipitation, river flow volumes and water levels in the channel and on the floodplain are vital for developingof stochastic event sets which represent reality, and the true relationship between rainfall and flow in each catchment. For EMDEs these are often only available for short periods of time or may be incomplete or inaccurate, and do not provide a reliable picture of long-term averages or extremes. Temporal density of observations on sub-daily (e.g., hourly) frequency is important to capture short-duration intense rainfall events. Spatial density of observations at rainfall stations are needed to understand rainfall patterns across large catchments. Gaps in either may prevent a model representing temporal and spatial rainfall patterns accurately. When using observation data consideration also needs to be made for changes in risk due to external factors (e.g., climate change and population/asset growth). Observations can also include assessment of the flood footprint or maximum flood extent. These can be derived from EO data, third party data sources and/or field mapping. However, these data may not always reflect the maximum extent and so some interpretation can be required. For example, the EO data available depends on the time of satellite image being taken, its overpass rate and the presence of cloud cover during the event.

- **Elevation and surface feature representation** is considered to be one of, if not the most, important influence on flood model accuracy because variations in ground surface elevation over short distances can greatly influence inundation depth and spatial patterns. Typically, current regional or national flood hazard models for DRFI use global DEMs at a resolution of 30-90m. The latest improved version of these is FABDEM although there are additional data sources which, when available, can provide greater detail (Figure 6). Whilst the quality of global DEMs is increasing this is still one the main limiting factors for flood modeling (see Box 4).

  Resolution of elevation data affects modeling of flow in a number of ways:

  » Representing the position and extent of river channels ('channel hydrography') and permanent water bodies to correctly simulate how water is routed through the river network, or retained in water bodies or floodplains. MERIT Hydro (Yamazaki, et al. 2019) provides a recent global hydrography dataset derived from MERIT DEM (Yamazaki, et al. 2017).
  » Representing high points or low points of small extents, for example ditches, berms, raised or lowered road or railways, which can block, re-route flow and cause ponding.
  » Representing features that affect channel hydraulics, including bridges can block and re-direct water during simulation, unless these are removed from the dataset.

- **Bathymetry data** describes the riverbed and is critical for understanding how water flows within rivers and is of particular importance for assessing fluvial flood risk. However, this data is often not available in EMDEs and therefore channel flow capacity must be assumed.

- **Environmental controls** on flood hazard are non-stationary, being affected by the changing natural environment, human influences on channel control (construction of dams or flood protection, dredging or lining of channels) and human influences on landcover (e.g., urbanization). These also impact the surface roughness of land which is an important control on flow speed and is usually accounted for by applying surface roughness coefficients, depending on the type of vegetation or built environment present. Obtaining up-to-date and high-resolution land-use land-cover maps is important for estimating roughness and how it varies, something that again is often not available for EMDEs.

- **Flood protection,** such as dams, and urban drainage can limit inundation within modeled areas, however representing these in the model is challenging due to the limited amount of data on location, design and standard of protection afforded by both physical flood protection and drainage networks, and decisions on storage versus release from dams. This is an even greater challenge for nature-based solutions and often these are modeled using a method similar to that for physical flooding protection – more research is required to improve the approach. Often broad and generalized assumptions are made to estimate the defended area and level of protection for fluvial flooding but the lack of data on drainage networks can be a critical issue in modeling pluvial risk. Attempts have been made to catalogue standards of flood protection and the most significant to date is FLOPROS (Scussolini et al. 2016).

- **Climate change** is a significant challenge for forward-looking flood models due to the need to model how region by region climate change will affect the seasonality, frequency and intensity of rainfall events and floods through changes in precipitation and temperature. Whilst there is considerable uncertainty in long term projections of climate change the Clausius-Clapeyron relationship (for every one degree rise in temperature the atmosphere can hold an additional seven percent of moisture) explains why flood risk is expected to increase in many locations.

  The effects of climate change on floods are being incorporated into flood models to estimate how flood risk will look in the period between 2030 and 2100. Model developers are producing 'climate-conditioned' views of future flood risk to assist decision-makers. Several approaches are emerging, using the outputs of global and regional climate models, which estimate climate conditions under each of several Representative Concentration Pathway (RCP) scenarios. The frequency or intensity of extreme rainfall and streamflows can then be adjusted in the flood model, such that extreme events are described with the expected frequencies they would occur with under future climate conditions, instead of the historical frequency derived from reanalysis data. An example of approaches to assessing future flood hazard is described further in Alfieri et al. 2015.

2.1.4 New approaches for flood modeling in data-scarce environments

As shown above, traditional methods for flood mapping utilize complex hydrodynamic and hydraulic models, which often incorporate shallow water equations (SWEs) in various dimensions (1D–3D) and require a variety of data inputs including flow rates, temperature, bed roughness, wind conditions, and more (Jovanovic et al. 2019). The extensive data requirement of these models limits their usability within data scarce environments.

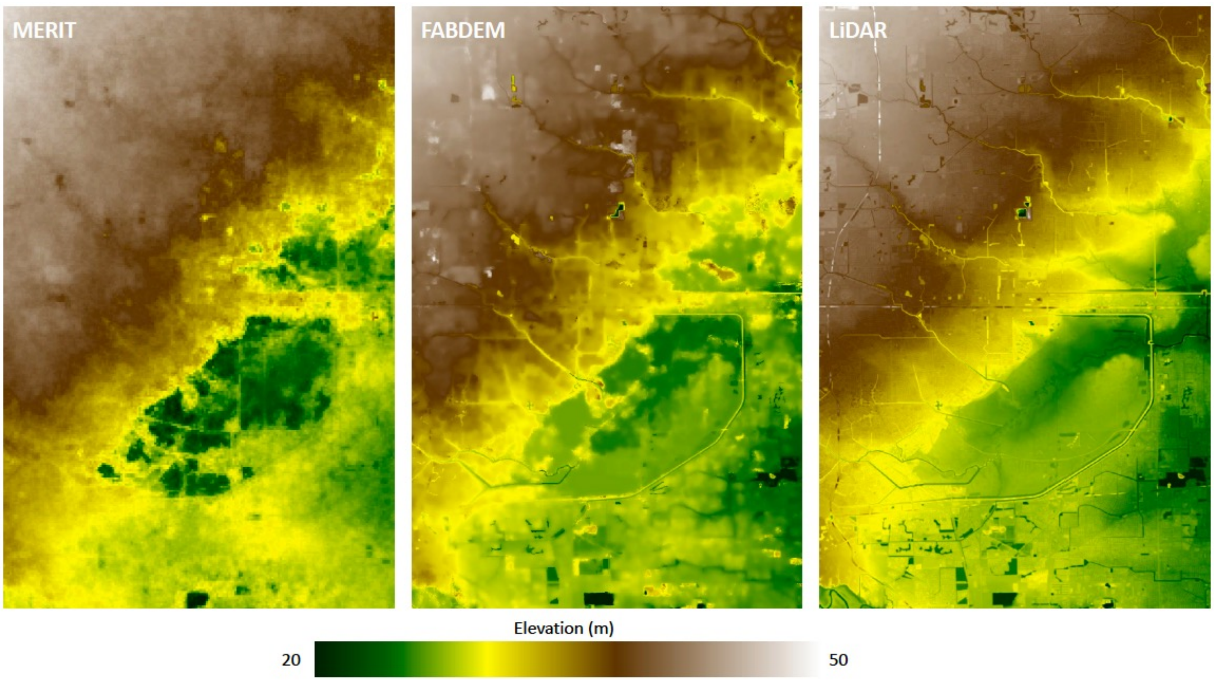
An alternative approach is to use simplified flood models, particularly the Height Above Nearest Drainage (HAND) model which has shown significant benefit in testing against traditional methods. The HAND model estimates flood extents by normalizing topography data through calculating the difference between the elevation of a land grid cell and the elevation of the river grid cell is estimated to drain into through flow simulations (Nobre et al. 2011).

In addition, newer approaches to global flood modeling combine new findings in hydrology and machine learning to predict flood extent and depth in data scarce regions based on climatologically and topographically similar areas where detailed data exists. However, it must be noted that sufficient flood maps developed from high-resolution flood models are required for training these machine learning models to produce good outcomes.

Figure 6: A comparison of elevation data around Houston, United States.

From left to right, the datasets show increasing resolution of data, in which natural (e.g., channels flowing from high ground) and artificial (e.g., road network raised with respect to surrounding land) features are increasingly well resolved, and therefore better represented as influences on simulated in-channel and overland flow in a flood model.

Source: Image reproduced with permission of Fathom Global.



Box 4: Improvements in topographic modeling and elevation data

Topographic modeling is a way of processing geographical survey data and is a critical component of flood hazard modeling. It represents the physical land-surface, including how height of the ground varies, and directly impacts how water will flow and accumulate over the ground. Topographic models relevant to flood modeling include digital elevation models (DEMs) and digital terrain models (DTMs) – DEMs often take into account surface objects (e.g., vegetation, buildings, etc.) whereas DTMs provide the true bare-earth elevation. For both of these the vertical accuracy of elevation data is critical.

Where LiDAR data is available it should be used to develop DEMs as it provides the highest degree of accuracy. However, LiDAR is very expensive to obtain and, when available, is often only for small areas of developed countries. Fortunately, the value of LiDAR data is increasingly recognized, and acquisition costs are reducing (in some cases similar to deploying survey teams to remote areas such as Pacific Islands). International organizations among others are funding more LiDAR acquisition in high-risk areas, including EMDEs, but coverage remains limited.

Until recently, where LiDAR was not available, the modeling community had been heavily reliant on data collected nearly 20 years ago by the Shuttle Topography Radar Mission (SRTM; Farr et al. 2007) for the creation of global DEMs. DEMs developed from this mission have improved greatly since their first release due to advancements in post-processing, however, they have numerous limitations, such as severe noise from radar returns in vegetated and urban areas and severely restricted vertical accuracy due to the original instrumentation. This has meant that significant quality assurance checks need to be run on the data, especially for flood modeling due to the need to capture influences on water flow and informal, local flood control information. Consequentially, any asset-scale analysis reliant on the accuracy of SRTM was itself limited, and the quality of terrain data held back progress in developing flood models for some regions of the world (Sampson et al. 2016).

The recent open release of Copernicus GLO-30 DEM from the joint DLR-Airbus TanDEM-X mission has finally shifted the status quo in global terrain data. With the open release of GLO-30, the scientific community has access to an updated view with much higher vertical and horizontal accuracy than SRTM. However, as TanDEM-X is a radar-based system like SRTM, it unfortunately exhibits similar limitations in vegetated and urban areas. Inaccuracy of elevation data in urban environments is of particular concern to many modelers because this is where hazard intersects most with assets and populations.

Thanks to machine learning techniques, new EO datasets, and the experience gained from working with SRTM, improved 'bare-earth' DEMs based on GLO-30 that attempt to tackle the inherent limitations are within reach. The first such improved DEM to be published in the academic literature is FABDEM (Hawker et al. 2022). FABDEM combines GLO-30 with other datasets using a machine learning framework that was trained against benchmark LiDAR data. The initial release of FABDEM yielded significant reductions in mean absolute errors across both urban and forested areas relative to GLO-30, and the DEM will continue to improve over time as new data and methodological refinements are incorporated. FABDEM is an important example of a new generation of DEMs that offer model developers in EMDEs the opportunity to significantly improve model accuracy, rendering models more useful across a wider range of applications.

2.2 Requirements and challenges with exposure data

To estimate the impact of flood hazard in terms of human or economic impact, exposure data needs to represent either the population or assets exposed to the flooding – at a suitable granularity for the required output. Exposure datasets describe: the distribution of population or different types of assets e.g., buildings, infrastructure, crop type etc.; characteristics relating to those assets (e.g., construction material, structure type); and the replacement cost of assets or a measure of income in the case of livelihood protection. Obtaining accurate information on exposure is a challenge, however, certain features of an exposure dataset are particularly useful for estimating flood losses and due to the localized nature of flooding, accurately representing the assets' locations is the most critical.

In terms of asset characteristics, construction material, occupancy type, number of stories, presence of a basement, ground floor elevation, floor/wall covering, and type of contents are most important. Accurate representation of ground floor elevation, as this can provide a threshold above which loss is sustained, as well as the presence of a basement and the spread of contents across floors can greatly influence loss. Beyond estimating the level of damage accurately, converting that damage into a loss estimate, is dependent on the challenging process of estimating accurate building replacement costs. The replacement costs used depends on whether there is a policy of replacing like-for-like, or so-called 'building back better' – improving the quality of destroyed buildings. Information on replacement costs should be well informed by local engineers.

The most detailed exposure data can provide characteristics per building footprint, based on ground surveys, or recording these details at address level. Capturing this level of data across large areas in developing countries is generally not feasible, and aggregated data is commonly used instead. Census data, global population, building footprints (e.g., Microsoft's Global Building Footprints) and settlement datasets (e.g., WorldPop) or openly available databases (e.g., OpenStreetMap) are commonly used. In the case of crop insurance, schemes are typically either purely parametric or based on yields compared to previous years, thus avoiding the need to try to estimate crop values which depend on highly dynamic prices.

Aggregated exposure datasets can also be developed using earth observation to delineate areas according to land use (e.g., rural, low density urban, high density urban). For each land use type the density and types of buildings can be sampled, and distributions of building characteristics, average occupancies, and replacement costs are applied to all cells of the same land use type. One source of land use data is ESA's WorldCover. Earth observation data is typically used in the development of "crop masks" for agriculture insurance, which identifies the cropland extent and area, and type of crop grown, or to identify areas of grassland or forestry.

Aggregated datasets are appropriate for use in flood risk modeling at national and regional scales, and can be used to develop risk transfer products, but to capture the influence of local variations in flood hazard the exposure data needs to be as high a resolution as possible and preferably at a similar resolution to the underlying hazard. Aggregate data can be based solely on global information, but the quality can be improved if national or subnational data are included to ensure the information matches local expectations and experience, as proposed in exposure modeling protocols published by the METEOR project (ImageCat Inc. and METEOR Project Consortium, 2020).[2]

2.3 Requirements and challenges in the vulnerability module

Vulnerability information relates the hazard intensity (usually flood depth) to a level of damage and loss (financial or other). For buildings and infrastructure, the amount of damage caused by a particular depth of inundation will vary depending on the speed the water is flowing, the duration of the inundation, the building type and within building types due to uncertainty in how that building will be impacted, and by extension differs by country due to different building stock characteristics (e.g., what the building is constructed from) and the presence and enforcement of building codes. Catastrophe models rarely consider water speed or duration due to vulnerability curves being defined almost solely based on flood depth, as claims and post-event damage surveys can most easily capture this metric.

[2] The METEOR Project can be accessed here: https://meteor-project.org/data/

In many data-scarce contexts there is very limited historical claims data, claims data that does not correlate with damage level (i.e., where a consistent relief payment is made based on a single threshold of damage), and a lack of comprehensive post-event damage surveys with which to develop empirical or analytical vulnerability curves. Instead, general or regional curves are often used. These include the JRC (Huizinga, De Moel, and Szewczyk 2017), or FEMA HAZUS vulnerability curves. There is significant uncertainty with applying such curves developed for the characteristics of floods and buildings in one region, to different areas within the region or another region entirely. For example, a general residential vulnerability curve may be developed for building stock dominated by two-story masonry buildings, and would not be relevant to a country dominated by single-story timber homes. Similarly, a curve may have been developed on the basis of slow-flowing, long duration floods, in which case it may not be suitable for mountainous locations characterized by fast-flowing floods. Investigations of how to improve this are ongoing, while the development of new country-specific vulnerability still lags behind the demand for risk models.

For crop insurance, linkages between flooding and crop yield may be derived from historical yield data collected by Departments of Agriculture, but creating a detailed relationship is often complicated by lack of precise information about flood depth, duration and extent.

2.4 Requirements and challenges in model validation

Validating a catastrophe risk model is critical to ensure it is fit-for-purpose to support DRFI solutions as well as for communicating with both the insurance market and client. However, validating a model in EMDE's is often particularly complicated due to the lack of historical hazard and loss data available. Where reliable data is available, flood models are usually validated by comparing simulated metrics against observed metrics for both:

- Individual model components - this can be done for the hazard (e.g., comparisons of modeled and historical data for precipitation/discharge/inundation depth, etc.), exposure (e.g., comparison of exposure distribution for different data sets) and vulnerability (e.g., comparison of vulnerability curves with damage survey data).

- Overall modeled losses by comparing estimated impacts (e.g., population affected, economic or insurance loss) for historical events, modeled Average Annual Losses (AALs), and modeled Exceedance Probability (EP) curves with the equivalents based on reported historical data. Validation of loss estimates often focusses on higher magnitude-lower frequency events as they typically provide a more accurate validation due to the systems of flooding overriding the uncertainties inherent in the model.

Such validation requires detailed historical data for river discharge, water levels and precipitation over an extended period of time (several decades) from gauges recording regular measurements in the river channel, and from event observations – either in-situ recordings of depth or EO-derived estimates of inundation extent. However, such records are often not available, are available for very limited number of locations in the area to be modeled or need to be controlled for changes in land use, climate or flood defenses over the time period of record (e.g., impact of urbanization on runoff potential). This lack of data makes it difficult to reliably estimate extreme events giving rise to large uncertainties in flood hazard and flood modeling. This issue is often most acute in low- and middle-income countries where the historical record of data and events can be very short or absent.

Impact estimates for historical events are often not available at the levels of accuracy or granularity required to validate the overall model. Improving model validation in these contexts relies on gradually improving event loss datasets (e.g., EM-DAT[3] and DesInventar[4]) and detailed records of event impacts in post-event reports (post-disaster needs assessment (PDNA), emergency response reports[5,6]), insurance claims data, and transparent accounting of damage and loss. Even where historical loss data is available it is likely to not represent the current risk, due to changes in the built and natural environment (including in exposure distribution and characteristics, asset value, and population) between the time of the observed loss and the present day. Trending of losses is applied to account for some of these changes but cannot account for all changes and this a common source of difference between modeled and observed losses.

[3] EM-DAT. The International Disaster Database https://www.emdat.be/
[4] UNDRR. DesInventar Sendai https://www.desinventar.net/
[5] GFDRR. Post-disaster needs assessment https://www.gfdrr.org/en/post-disaster-needs-assessments
[6] GDACS. Global Disaster Alert and Coordination System https://www.gdacs.org/Alerts/default.aspx

Photo credit: Wulandari Wulandari / Shutterstock.com

3. Applying earth observation to improve flood modeling

Earth observation data has great potential to improve flood modeling. Improvements in satellite technology, including an increasing number, resolution and type of sensor, and an increasingly long historical period of data available, is enabling EO to become of greater use for the assessment and monitoring of flood risk. The benefit EO data brings to the model validation process is already apparent and an area of significant use.

Using earth observation data to improve flood models is an area where there has been and will continue to be lots of progress due to the advantages EO data has over physical models, in particular for parametric solutions. This is because they are (i) observing floods so there is no need to separate the source of flooding (i.e., pluvial vs fluvial), (ii) the effect of anthropogenic infrastructure is inherently captured in the resulting flood extent, and (iii) it avoids errors that can be introduced by using auxiliary data sets. However, there are several challenges when using EO data for flood modeling and triggering DRFI instruments:

- Earth observation data is only available for a limited historical period which is often not sufficient to develop extreme value distributions.
- The images captured by satellites do not coincide with the peak flood presenting a challenge with defining the event footprint accurately.
- Satellites often capture an incomplete view of any flooding taking place as the swath width (width of the satellite image) is unlikely to match the width of the flooded area which is often greater.
- The presence of vegetation and/or buildings can lead to scatter where the radar signal is scattered in many different directions leading to a weak signal.
- Insufficient accuracy of water detection algorithms used to derive flood extents leading to confusion where surfaces such as tarmac or burned areas are mistaken for flooding. However, advances in machine learning and computing power are enabling the processing of much more historical EO data thereby improving the detection algorithms.
- Clouds obfuscating an image (a particular issue for optical satellites).
- The basis risk (Box 5) present due to the inconsistency of using earth observation data to trigger a product but not develop the original index.
- The need to calibrate the EO data using gauge data and weather stations which are often not available.

Box 5: Basis risk

Basis risk is the difference between an index and a specific portfolio of losses and occurs when the client's loss experience does not match the payment from an index-based product (e.g., parametric policy). This risk can be negative (i.e., the insured does not receive a payment when actual losses should have triggered a payment) or positive (i.e., where the insured receives a payment even if actual losses are lower than the trigger) and is generally higher for EMDE's due to the difficulties in validating a model.

In addition to basis risk, one needs to consider the perception issues associated with a misunderstanding of what a policy is covering (i.e., what is being excluded from the insurance contract). This is relevant for both parametric and indemnity insurance solutions.

Given the limitations associated with EO data, in particular the short historical time series, EO data is unlikely to be of great value for developing a full risk profile to support the design of DRFI instruments in EMDEs. Instead, it holds greater potential for the development of risk transfer structures at lower return periods where flood models are seen to be weaker and 20-30 years of data is more likely to capture relevant extreme events. It is also likely to be of most benefit in rural areas where flooding is of relatively long duration (i.e., flooding remains for several days) and dominated by rivers. Further work needs to be done to fully understand its value and limitations for use in urban areas and for pluvial driven events given the constraints mentioned in this report. Cloud to Street demonstrated the potential application for an EO-driven approach in their solution to provide parametric debt relief for farmers in Colombia (see Case Study 1).

As the historical EO data record increases and flood modeling advances future efforts may be able to leverage the strengths of each for assessing risk as well as structuring risk transfer products (i.e., assessing a wider spectrum of events below the 1-in-20-year return period which is the point at which models usually start). In most cases a longer duration of historical events are required to create a satellite-derived flood insurance index based on hazard footprints but a promising approach using Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data has been trialed along river basins in Bangladesh and Argentina where the lack of gauge and observation data makes physical flood modeling highly uncertain.

Case Study 1: Earth observation used to develop parametric insurance for small and midsize farmers in Colombia

The Agricultural Bank of Colombia (Banco Agrario de Colombia), in partnership with Cardif Seguros Generales, commercialized a parametric insurance product developed by Raincoat that provides protection to small and midsize farmers across Colombia for the perils of excess rainfall, drought, and flood (Banco Agrario 2022). This coverage was innovative for its ability to provide flood coverage across the entire country of Colombia, and its lack of exclusions for geographic area, or nature of underlying farming activity. This allowed farmers from all municipalities across the country to access the insurance coverage.

The flood component of the coverage was developed with the flood intelligence platform Cloud to Street. Cloud to Street uses satellite and environmental data to monitor and map historical and near real-time (NRT) flooding. The Colombian parametric cover utilized two flood indices: one based on observed flooding and a second based on satellite precipitation.

The observed flood index was developed using Cloud to Street's water detection Convolutional Neural Network (CNN) and NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Aqua and Terra satellites. Every MODIS image taken over the country of Colombia since 2002 was used to create the index. Probability distributions were then used to estimate the exceedance probability of past events using annual maxima for the observed flood index for each municipality. Thresholds were chosen from the probability distribution to achieve an expected loss consistent with the pricing of the policy, and were back tested with the data archive. For added certainty, the Colombia cover utilized a secondary precipitation trigger (calculated for each watershed) to minimize potential negative basis risk events where the MODIS satellite may not adequately capture flooding. Thresholds were calibrated for the precipitation index separately, and these were used as an or trigger, whereby exceedance of set parameters by either the MODIS index or the precipitation index would lead to a payout.

To ensure sufficient accuracy for pricing and low basis risk for triggering payouts, the performance of each index and thresholds were validated against flood damage data reported by the governmental agency Unidad Nacional para la Gestión del Riesgo Desastres (UNGRD) in Colombia. This process ensured that the two indices used captured all major historical events.

Today, the entire country is being monitored daily to determine in near real-time if index thresholds have been exceeded in any municipality. The methods in this product relying on the growing archive of satellite data for both index creation and monitoring proved novel among parametric flood covers. Its success in Colombia further illustrates the ability to structure parametric flood coverage for both private and humanitarian purposes around the world using satellite earth observations.

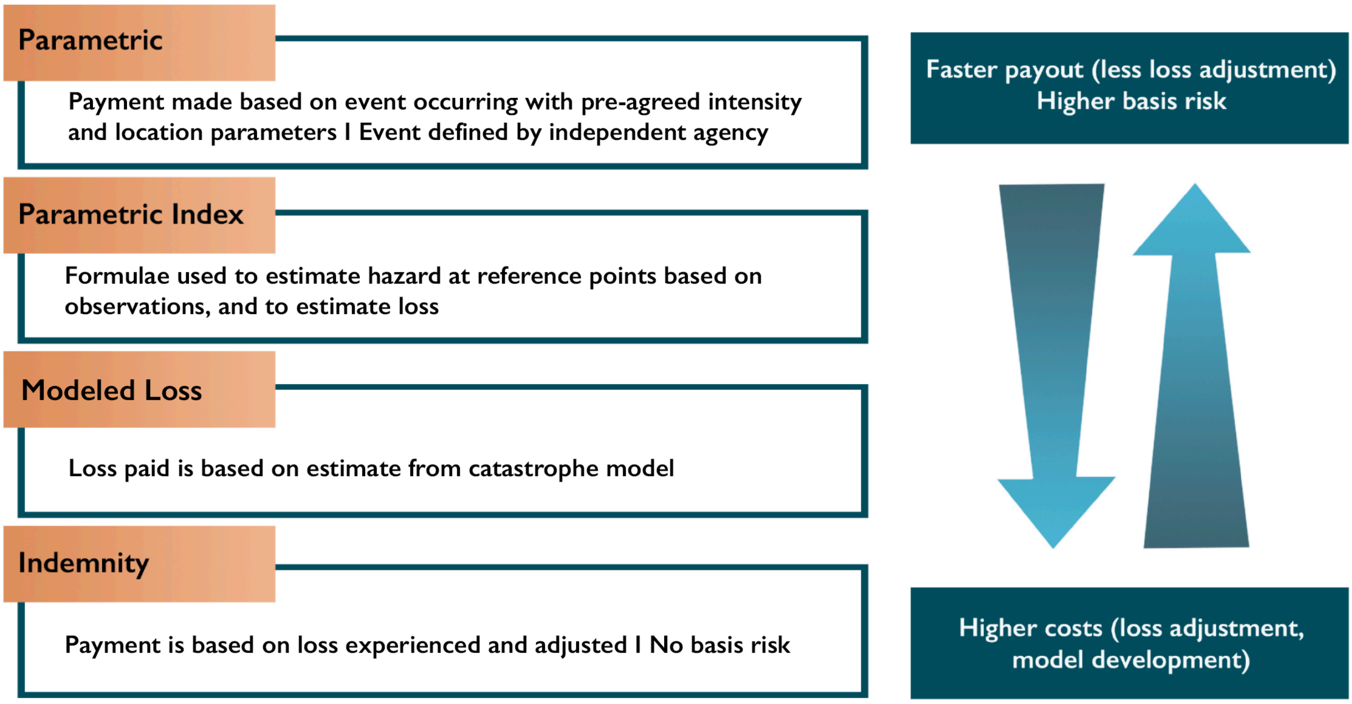
4. Risk transfer requirements of flood modeling

Low-income countries typically lack financial protection against the impact of disasters at either household or national level. This leads governments to rely on coping measures such as budget reallocations and donor assistance to fund response and recovery, which are less efficient due to the time required to secure borrowing and the additional cost of relying on these measures for moderate to large events.

Pre-arranged ('ex-ante') DRFI solutions can provide greater financial resilience, increasing the ability of national and local governments, homeowners, businesses, and low-income populations to respond to and recover from disasters more quickly and effectively while also incentivizing greater physical and societal resilience. Ex-ante solutions can also be provided at a lower cost than arranging ex-post borrowing, where the beneficiary often has less time and bargaining power in the aftermath of a disaster. Insurance is one ex-ante DRFI solution that provides financial protection against natural hazard events.

Figure 7: Summary of insurance products.

Source: Adapted from Willis Towers Watson (2017) and IDF (2017).



There are a range of different insurance products that can be used to transfer risk (see Figure 7). Indemnity structures provide the client with the greatest confidence that any pay-out will be equivalent to the insured damage. However, they are typically slower to pay out than parametric solutions, require robust claims management systems and a modeling solution still needs to be used to estimate and price the risk. For parametric solutions, the complexity of the product needs to match the available data and risk modeling; where fluvial flooding is dominant and exposure is broadly distributed a parametric index-based product has benefits due to its transparency, simple trigger mechanism and no requirement for detailed exposure data. A modeled loss approach can incorporate multiple data inputs (model data, measurement stations, gauge data, earth observation data) to calculate a consistent estimate of flood risk and mechanism to trigger payout. However, this requires good exposure data and high levels of model calibration and validation. If good data is not available then an alternative approach to triggering a payout is to use more widely available and simpler metrics such as people affected rather than economic damage.

Parametric products are of particular interest to governments due to their rapid speed of pay-out, transparency and relatively lower costs compared to many indemnity-based schemes which can require lengthy claims assessment processes. Several sovereign parametric solutions exist for tropical cyclones, earthquakes, and excess rainfall. However, there have been very few sovereign parametric solutions established for flood, due to the more complex nature of monitoring flood events and triggering payment in (near-) real-time, and the lack of data in low- and middle-income countries with which to develop and validate flood models to support parametric design.

In certain circumstances it is possible to use an excess rainfall index as a proxy for flooding. Excess rainfall insurance provides protection against losses associated with heavy rainfall events occurring over a short duration. They have been offered by the African Risk Capacity Limited (ARC) and the Caribbean Catastrophe Risk Insurance Facility (CCRIF) to their member countries. Pay-outs associated with these products are triggered by an estimation of the intensity of rainfall, using satellite-derived rainfall data and weather station data. Historical rainfall records and asset information (distribution and susceptibility to flood damage) are used to develop a parametric index that defines the probability of rainfall intensity and associates this with financial loss. A loss threshold is identified between the cedant (the entity who benefits from the insurance) and insurer and based on the index the corresponding rainfall threshold is identified. When rainfall data shows this threshold is exceeded, the product is triggered, and an insurance pay-out is required.

To determine an appropriate index, the amount of rainfall over a period of time needs to strongly correlate with financial loss. In simple hydrological environments this may be a suitable assumption. However, this approach is not feasible in countries or areas with a complex hydrological network, i.e., where rainfall in one location can't be directly linked to the extent or severity of flooding in that or other areas. This is due to the relationship between excess rainfall and fluvial risk breaking down as catchment dynamics change in scale and climate - factors affecting this will include topography, catchment size and tropical & sub-tropical environments that experience more evapotranspiration. To determine the risk in these locations a direct index is less suitable, and a flood model needs to be used.

The placement of a risk transfer instrument requires the sponsor/cedant to be satisfied that the structure of the instrument supports its requirements and that it is correctly priced in relation to the trigger mechanism. A further requirement is that the model is of sufficient granularity and accuracy to be accepted by the insurance market as they believe the risk estimated by the model reflects, as well as possibly, the true risk. Without this, insurers may not be willing to underwrite the risk (i.e., the product may not be 'placed') or they may not make it available at a cost ('premium') that is affordable to the cedant.

All indemnity insurance solutions and most derivative products require the flood model to provide a realistic representation of the risk. The model output is one of several inputs an insurer considers when determining whether to accept the risk and in setting the associated premium or 'price' which is often loaded to take into account uncertainty. The insurance industry's acceptance of a solution can often be determined by their confidence in the organization who developed the model, with additional criteria (e.g., detailed documentation and access to the model) being applied if the organization is less known to the market and if alternative models aren't available to provide an independent view of risk. The model must fulfil certain criteria including being built using scientifically defensible methodologies and high-quality data; built in a standard industry format; able to quantify both risk and uncertainty; have been fully calibrated and validated against historical experience, accounting for climate impacted trends that may require adjustment of historical experience, and be reasonably up to date (i.e., the model incorporates recent scientific advancements and up to date historical data). Flood models also need to estimate the uncertainty in any loss output to enable the design and pricing of risk transfer products and instruments may be chosen to reduce the amount of uncertainty in the final solution (e.g., population impacted doesn't require complicated, and often unavailable, vulnerability data to be incorporated into the model).

Certain parametric insurance solutions (e.g., those using modeled loss triggers) result in further requirements of the flood model because the triggering process relies on using the model to estimate a loss; the solution triggers if that modeled loss exceeds a pre-agreed threshold. Whatever the trigger mechanism, the monitoring and assessment process must be consistent with the risk modeling used to set the trigger thresholds as any inconsistencies increase the risk of the loss sustained being higher or lower than the estimated loss.

5. Monitoring flood risk to trigger DRFI products

Flood monitoring describes the real-time assessment of rainfall or flow conditions to inform forecasts of potential flooding, trigger flood warnings, or trigger DRFI instruments (parametric products are triggered by the exceedance of a pre-agreed quantifiable parameter). This contrasts with flood modeling, which is generally performed independently of an event occurring to assess risk.

Flood monitoring may comprise in-situ (automatic or manual readings from rainfall and flow gauges) and/or remote sensing techniques. In terms of DRFI and DRM, monitoring is a vital element for triggering ex-ante risk financing and anticipatory action (Box 6). Satellite-derived flood extent data, river gauge data, forecast tools and/or flood models can all be used to monitor flood inundation across a geographical area and/or determine whether an event has triggered a pre-agreed parametric threshold for a pay-out to be made.

Box 6: Flood risk forecasting

Flood risk models and the tools to monitor whether flooding has triggered a parametric policy can support more than just DRFI solutions. They can also be used to support anticipatory action to provide households forecast to experience the impact of extreme events with effective cash transfers before an event occurs.

The ability to provide flood forecasting capabilities is important to inform users of upcoming hazardous weather conditions and the potential impact these may have on any relevant financing instruments. Flood forecasting tools, such as JBA's Flood Foresight, use the latest forecast precipitation data (e.g., European Centre for Medium-range Weather Forecasts) and a rainfall-runoff model to calculate streamflow conditions and identify potential areas of flooding. This approach enables the model to output daily probabilistic forecasts for flood extent and depth with an approximately 10-day lead time. The same monitoring tool can also use observed streamflow data from river gauges along with actual precipitation data to produce estimated flood extents and depths, but these will have a shorter lead time.

5.1 Data types and monitoring conditions

The type of parametric product (e.g., pure parametric or modeled loss) will determine the granularity and type of data required for monitoring conditions and triggering pay-outs. For example, a pure parametric product could be designed to trigger based solely on water levels in major rivers measured using gauge data, or amount of precipitation falling on one or more rain gauges. Simple exposure and vulnerability datasets may still be required in the product design, to understand how the physical hazard relates to potential impacts and estimate basis risk, but these can often be simpler datasets than would be required for other types of DRFI solution. For example, a modeled loss trigger requires not only observation data, but also requires the same risk model and exposure and vulnerability data used in designing the solution, to be re-analyzed with data representing the current event to estimate the loss and confirm whether it exceeds the trigger threshold.

The selection of a trigger mechanism needs to consider reliability of the monitoring system (e.g., will it be operational when required) and the accuracy of its measurements. The transparency of the measurement process is also crucial to ensure objectivity and independence in the trigger process, i.e., is there a risk of moral hazard such as biased reporting to influence a product triggering, and can the measured values be corroborated independently.

5.2 Monitoring flood extent

A common approach to monitor flood extent is to use near real-time and/or forecast rainfall and flood data from satellites, measuring stations and river gauges maintained by an independent agency, either directly as a trigger or as an input to the flood model to simulate near-real time streamflow conditions and inundation. Such models can be continually executed as new data is received to ensure the flood is monitored in as close to real-time as possible and forecast potential flooding (See Box 6). A challenge with input data is that certain preliminary precipitation datasets (e.g., the Global Precipitation Measurement Mission) can be very different to the final confirmed datasets, which needs to be considered at the outset of finalizing the calculation agent process.

Technology innovations are making the process of monitoring flood extent and therefore triggering risk transfer products more accurate with two notable innovations being:

- EO data, possibly in combination with additional third-party data (e.g., from social media or digital records of currently manually recorded sensor data), can be used to identify flood inundation during and after the flood event. This EO driven approach was used for the triggering of pay-outs in the Bangladesh and Argentina trial completed by Tellman et al. (2022)

- Global multi-sensor satellites providing near-real time data and/or smart sensors (Box 7) located at critical locations or on important assets to directly measure flood depth at desired locations.

Box 7: Flood Flash

Flood Flash is an innovative company that has recently entered the insurance market. The company's product is based around the benefits of parametric cover for supporting businesses' recover from flood events and uses a sensor to determine flooding and trigger a pay-out for a parametric insurance policy.

The insurance policy works by agreeing a set pay-out when a certain depth of flooding occurs. The prevalence of flooding is measured by the company's mobile-connected sensor which is installed on the property and records the depth of water to a high level of accuracy. If the sensor records a flood depth greater than the agreed trigger threshold, then it automatically alerts Flood Flash, and the claims process begins. This involves *Flood Flash* verifying the claim and paying out the agreed amount.

Flood Flash pays the majority of claims within 48 hours, hugely decreasing the time from flood to payment experienced in traditional indemnity and parametric solutions.

Case Study 2: SEADRIF Insurance Company's flood product

SEADRIF Insurance Company is a licensed insurance company, fully owned by its member countries. With financial support from development partners, the company can provide disaster risk financing and insurance products to participating countries, with the potential to become a regional catastrophe risk pool. SEADRIF's first catastrophe risk insurance product provides Lao PDR with cover against flood risks. The insurance product combines innovative modeling approaches to support the placement of a sovereign parametric insurance product with Deltares, CIMA, EU Space Agency, European Centre for Medium-Range Weather Forecasts and JBA all contributing to the final product.

The stochastic model, which includes fluvial, pluvial, tidal and coastal flooding, was developed to have the same features as the simulated historical time series and was compared with historic events to ensure a close representation. The model was used to develop a risk profile for Lao PDR and was inter- linked with the stepped trigger mechanism based on population impacted, in an effort to limit basis risk.

To monitor the flood risk and assess whether a flood had triggered the policy a flood monitoring tool was developed. The approach used is based on having a database of pre-simulated flooding scenarios that correspond to return period hazard maps of water depth based on the stochastic model, and during an event the available information from gauge data, simulations and earth observation data is used to select the most representative map for each subarea and each type of flooding. Once a mosaic of maps has been selected this is overlaid on a population density grid to understand total impact in terms of number of people affected.

Two key innovations in the design of this product were:

1. The inclusion of satellite observation data during an event to supplement the stochastic model output and representative gauge data. Flood extents are derived from Sentinel-1 data and compared on a pixel-by-pixel basis to the flood footprint from the hazard maps with a similarity index being used to supplement the hazard maps with EO data. Whilst including EO data did increase the risk of a pay-out being triggered for events that would not have been triggered based solely on modeled output, reinsurers saw this as a beneficial innovation and one that is expected to see further use in the future.

2. The Flood monitoring tool developed by CIMA, Deltares, LIST and Fadeout Software, which hosts the Near Real-time Analyzer and Web interface. The tool identifies the affected population, which is used to assess if the trigger thresholds for the insurance policies are exceeded and pay outs are to be made. The Near Real-time Analyzer generates an estimate of the number of people affected based on input data from in-situ gauges, satellite data and hydrological/hydraulic model flood forecasts. Access to the tool provided reinsurers much needed confidence in monitoring the flood event and managing the claims if triggers are exceeded.

The placement of the product required patience as whilst reinsurers were very interested in participating, they had several questions on both the technical and practical implications. This led to significant peer reviewing of the concept and product, discussions and deliberation to understand the product, and estimation of the uncertainty associated. Through these discussions SEADRIF Insurance Company was able to ensure several reinsurers were satisfied with the product design and modeling methodology and participated in the reinsurance placement.

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6. Reconciling risk transfer requirements with flood modeling: Approaches for modeling risk transfer solutions in data-scarce contexts

For developing countries flood risk is often the most prevalent natural hazard with approximately 90 percent of the world's flood-exposed people living in low- and middle-income countries with many of these people also facing extreme poverty. The potential for flooding to cause damage is heightened in developing countries due to the lack of infrastructure systems – including drainage and flood protection - and often unplanned construction. The impacts are only going to become more frequent and severe due to climate change and continual growth in exposure at risk. This has led to increasing interest in developing risk transfer solutions to financially protect homeowners, companies and governments. A diverse range of modeling and analytical approaches have been developed to support risk transfer solutions. However, in some cases it has been difficult to place a financial instrument in the international insurance market or the premium has been high due to the risk modeling approaches used not being accepted by the market.

Successful flood risk transfer solutions ensure the instrument is placed with a risk-related premium and robust trigger mechanism, whilst minimizing basis risk for the sponsor and insurers. Key considerations to enable successful placement are outlined below, under the themes of 'Risk modeling', 'Product structure', 'Monitoring events and triggering payouts' and 'Communication'.

6.1 Risk modeling

The two critical requirements of a flood risk model are:

- Being able to quantify risk and uncertainty using scientifically defensible methodologies.
- Having all its components and the overall losses calibrated and validated using the best available data.
    - » Including how loss estimates and hazard frequency and intensity compare to historical records, and how well asset values, attrubutes and vulnerability reflect reality.

Additionally, to place a risk transfer instrument in the market the model needs to be accepted by the insurance industry. To do this the model should be:

- Built using a standard insurance industry catastrophe model framework.
- Granular enough to determine differences in flood impact across small geographical areas.
- Regularly updated to reflect recent significant events in their event set, updates in flood modeling approaches and to reflect latest riverine, environmental and climate conditions.

More generally when using flood risk models to estimate flood risk under future climate conditions, users should seek to understand the approach taken to adjust event sets and be comfortable that uncertainties in projected risk estimates are clear and well communicated.

6.2 Product structure

When designing a risk transfer instrument consideration should be given to:

- The modeled loss estimates, and the benefit of an insurance solution compared against other DRFI instrument options (e.g., contingent finance).

- Whether an insurance solution needs to be incorporated into a wider risk layering approach, and the benefits of parametric, indemnity and modelled loss approaches on a case-by-case basis.

  » The choice of solution can be influenced by the type of flooding, available data, and intended purpose and beneficiaries.

When it comes to more detailed decisions such as the coverage amount, deductibles, attachment and exhaustion points, and whether the pay-out is linear or stepped, a balance is needed between the client's requirements and the risk profile. For example:

- Where the level of risk differs significantly across the target area the product needs to account for these variations.

- Pay-out structures for a parametric policy should address the potential for significant increases in loss for a small change in return period, possibly by using a stepped, or gradually increasing pay-out structure, which can also help with the management of uncertainty.

- Deductibles (for indemnity products) and attachment and exhaustion points (for parametric products) should be set according to the amount of coverage required, how much financial protection is already in place and whether the region is dominated by high frequency low severity events, or vice versa.

6.3 Monitoring events and triggering pay-outs

For parametric products, a suitable monitoring approach is needed to ascertain, quickly and impartially, whether an event has reached the agreed thresholds to trigger a payout from the risk transfer product. This includes:

- Combining modeling, gauge data, and EO data for:

  » Redundancy of data sources and cross-validation of event characteristics.
  » To enable timely remote triggering (not solely reliant on manual checking of gauges which introduces moral hazard).
  » Minimize limitations of EO data such as gaps in coverage due to overpass rate and cloud cover.

- Minimizing basis risk to acceptable levels for both the client and insurer.

  » The insurance industry sees EO data as one of the most promising innovations to address the challenge of accurately determining flood extent and depth. Though EO data often provides accuracy in triggering parametric solutions, the data is often not used directly in determining the risk profile, which introduces inaccuracies between the modeling and monitoring approaches.

- Having one or more independent well-established agencies act as Calculation Agent to publicly report on event occurrence and determine whether a payout should be triggered.

6.4 Communication

To minimize the disconnection that can occur between developing a model and placing a product in the market, there needs to be high levels of communication and collaboration between all parties involved in a transaction, including:

- Achieving a balance between the technical aspects of the model and product to adequately cover the risk, and the ability of a client to understand the processes and limitations, and potential for payout.

Good communication and transparency in a phased approach can engage stakeholders early in the process and feed important local information into the model design as well as to promote understanding of:

- The data that is being used and not being used (e.g., local data may not be used due to moral hazard or non-homogeneity across the historical time series).

- Why this data may give different results to their expectations based on experience or understanding of the product.

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7. Summary

This report summarizes the state of the art of flood loss estimation for disaster risk financing and insurance. It places DRFI in the context of wider disaster risk management, for managing the residual risks after the effect of FRM strategies. In presenting an overview of catastrophe modeling for flood, we demonstrate the complexity of these models and their data requirements. The main challenges with flood modeling center on data availability and data quality. However, as the report shows the quality of modeling is not the only component determining successful placement of a flood DRFI product in the market, with transparency, communication and trust in the product (which includes trust in the modeling) all key factors.

By laying out the requirements of the international (re)insurance market to use a flood model with confidence, this report signposts key areas in the design of flood risk modeling and flood DRFI projects for data-scarce contexts. Key requirements include the use of a probabilistic catastrophe model framework, ability of the model to represent the true risk as well as possible, this being demonstrated through whole-model validation, and clarity on the assumptions and limitations, in particular where global data are applied and in application of vulnerability curves from other regions. In designing parametric solutions, availability of data and systems for independently monitoring events and triggering pay-outs is crucial, as is the design of a structure that meets the client's needs and provides efficient use of capital. No matter the quality of the technical work that goes into design, effective communication with the client is vital to ensure understanding of the benefits, processes and limitations of the product.

The guidance in this report has been informed through consultations with insurance industry and development sector practitioners including with flood hazard and risk modeling experts, underwriters and brokers, and earth observation specialists, who were able to comment on state-of-the-art processes, key challenges, and innovations in overcoming those challenges. The guidance should be considered by those commissioning flood models for DRFI purposes, to develop greater understanding of the technical and non-technical needs of such projects as well as those working on trigger-based modeling in adjacent sectors (e.g., climate resilient debt clauses).

As a next step the World Bank and Insurance Development Forum will look to identify how the recommendations contained in this report can be applied to real life contexts including through a series of case studies.

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