NOTE 2a

Flood Risk Modeling

Floods are typically characterized as one of three types: fluvial (river flood), pluvial (surface water or flash flood), or coastal[1]. Each type can cause impacts to people, assets, and governments; and for each type, climate and disaster risk financing (CDRF) mechanisms can build financial resilience to risks that cannot be cost-effectively mitigated or avoided. Nevertheless, these flood types manifest very differently, and these differences affect both the risk modeling approach taken and the risk financing mechanisms that will be most feasible and effective.

Of the three types of flood mentioned above, two are most common:

Photo Credit : Dibakar Roy/pexels

Fluvial flooding. Such flooding occurs when a river can no longer carry the volume of water within its channel and overtopping occurs. The severity of this flooding is driven by a range of factors, including the total volume of rainfall (or snowmelt) within the catchment, catchment characteristics (e.g., soil moisture conditions, soil type, landcover type, and topography), groundwater conditions, the river channel network's capacity to transport the water (e.g., the shape of the channels, any blockages, etc.), and any flood protection and water management infrastructure in place (e.g., dams, levees).

Photo Credit : Dibakar Roy/pexels

Pluvial flooding. A result of flash flooding and storm runoff, pluvial flooding occurs when high-intensity rain falls over a specified area and overwhelms the drainage capacity of the ground and/or drainage systems. While pluvial flooding can create "ponds" in small depressions, on steep ground it can cause a fast-moving flow of water across the ground.

These two types of flooding can occur independently of one another, but flood events often entail both pluvial and fluvial flooding, and differentiating their impacts can be difficult.

Like the catastrophe models for other perils, flood risk models for CDRF applications combine modules on hazard, exposure, vulnerability, and loss (see Note 2 on catastrophe risk modeling for more details). The hazard modules for fluvial flood and pluvial flood modeling are described in more detail in the following two sections. Exposure and vulnerability modules are also important considerations for determining the feasibility of flood risk modeling and insurance, and for gathering and preparing data:

[1] There are other sources of flooding as well, including dam breach, tsunami, groundwater, spring melt, and glacial lake outburst floods.

Exposure module:

A key consideration for flood risk is the availability of geographically granular exposure data, since flood hazard can vary substantially at granular spatial scales (e.g., on the same street, two houses may face substantially different risk of fluvial flooding depending on their distance from the river). Thus the exposure data for flood risk modeling must be far more detailed than data for other perils, such as earthquakes.

Vulnerability module:

The types of impacts that are being modeled are important. For impacts to buildings and infrastructure, generic regional vulnerability curves are available (e.g., Joint Research Centre [JRC] flood depth-damage functions[2]); but structures may vary substantially in their vulnerability based on a range of characteristics (e.g., number of stories, first-floor elevation, etc.). For such assets, vulnerability is typically modeled as a function of flood depth, though floodwater velocity and duration of flooding can also be important determinants of impacts (typically not captured in catastrophe models). In agriculture, flood timing is important for impacts, as crops are vulnerable to different flood depths and durations at different stages of their life cycle.

Fluvial Flood Hazard Modeling Approaches

Flood modeling is particularly challenging because flooding is a highly localized peril that can impact assets in various ways. Flooding is heavily influenced by the built environment and by the impact of humans on the environment.

Typically, hydraulic models are used to understand the potential for flooding (inundation) across an area of interest. These models take as input the volume of water flowing through the river channel (discharge), and they simulate the influence of channel dimensions, roughness, and flow controls on the movement of this water. If the model determines that the volume of water entering a section of the river exceeds its possible capacity, then the model will simulate the quantity of water that overflows the riverbanks, the locations where overflow occurs, and the distribution of the overflow based on a digital elevation model (DEM)[3].

To determine the flow of water in the river, along with timing and peak volume of extreme flows, two alternative approaches are used:

1 Historical data based on river gauges:

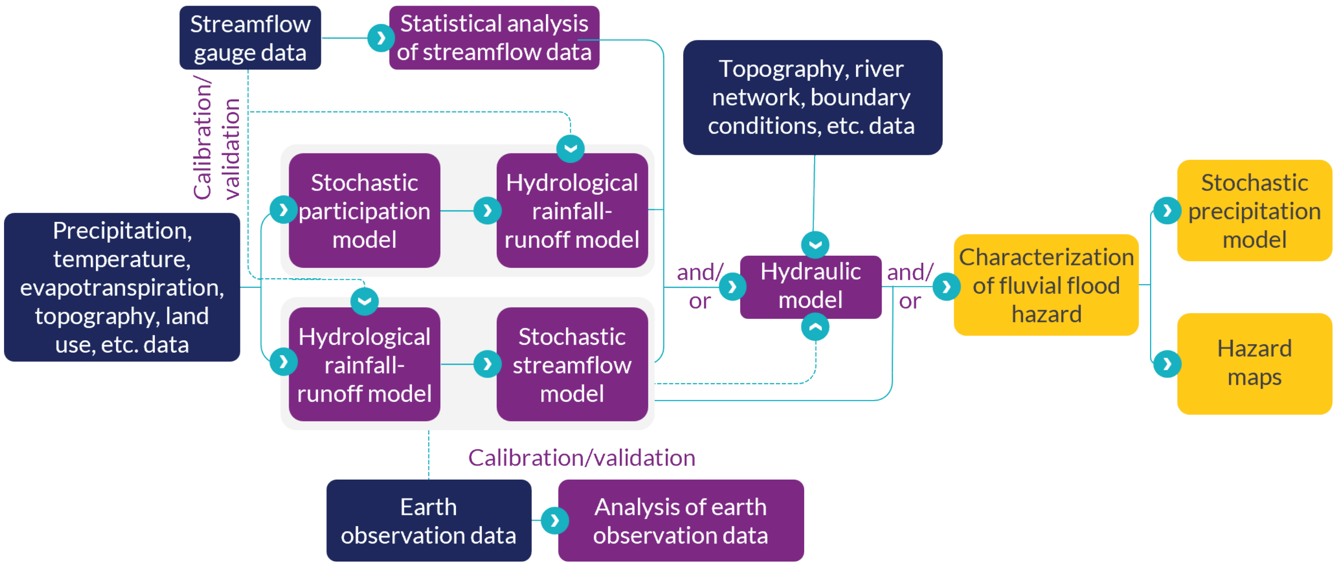
River gauges monitor the flow of water (also called discharge or streamflow) and enable the extrapolation of historical data using statistical techniques. This approach often provides the more accurate representation of events but requires at least 30 years of historical water-level and discharge data, which are often not available in developing countries.

[2] J. Huizinga et al., Global Flood Depth-Damage Functions: Methodology and the Database with Guidelines, EUR 28552 EN (Publications Office of the European Union, 2017), doi:10.2760/16510, JRC105688.
[3] A digital elevation model (DEM) is a 3D representation of the "bare earth" surface of land shown without tress, buildings or other objects.

2 Rainfall-runoff models:

Sometimes called hydrological models, these estimate the flow of water from meteorological data (mainly precipitation and temperature) and catchment characteristics. They do this by routing water that falls within each catchment to its associated river, but they rely on computerized representations of the catchments, which are often overly simplified.

Figure 1: Sample approaches to characterizing fluvial hazard



Source: Alastair Norris et al., "Flood Risk Modeling to Support Risk Transfer: Challenges and Opportunities in Data-Scarce Contexts," World Bank, 2023, https://documents.worldbank.org/pt/publication/documents-reports/documentdetail/099255511072316127/idu01dab70bb0f83b04d830b5460a05f6c3f5775.

Pluvial Flood Hazard Modeling Approaches

Pluvial flood modeling follows a similar approach to fluvial modeling but focuses on estimating the volume of water collecting at low points within an area. The model seeks to identify the amount of rainfall that occurs over different durations with a given probability. This information provides a range of possible precipitation events and acts as an input to the hydraulic model, which simulates flood depths for different return period events.

In countries where flooding is generally confined to the area where the rainfall has occurred (e.g., small island states without large catchments or long river networks that transport the rainfall long distances), pluvial flooding is often the main type of flooding.

Depending on the use case, in some instances it may not be feasible to model the flood depths associated with pluvial flooding. Instead, analytics for pluvial flood would focus primarily on modeling the rainfall itself. This approach to modeling pluvial flooding is sometimes referred to as "excess rainfall," as it considers the volume of rainfall above which flooding would be expected within the same area.

New Approaches to Flood Modeling

Two recent innovations in flood modeling are worth mentioning in this note. The first is the advent of global flood models, which combine new approaches in hydrology with machine learning to predict the potential flow of water in regions that lack data. These models work by selecting regions that are similar to the region of interest in terms of climate and topography and for which detailed data exist and then transferring this knowledge to the data-scarce region. While this approach provides significant opportunities to analyze previously unmodeled regions, it is important to note that these models may not have been calibrated and validated locally for all countries. The need for validation is an important consideration when applying data from these models.

The second innovation is the use of Earth observation (EO) data (sometimes called remote sensing data, or, depending on its source, satellite-derived data) to support the assessment and monitoring of flood risk. EO data have great potential going forward: they are available at scale more cost-effectively than any localized measurements, they can estimate various key parameters (rainfall extent, inundation extent, etc.), and their accuracy and resolution are improving rapidly. EO data will be an important area of research in the coming years, initially for the monitoring of flood events and then for providing historical time series for determining flood risk profiles, in particular for events with shorter return periods, where models are less accurate. However, Earth observation data have some key limitations, including infrequent overpasses (when the satellite observes a given location), incorrect definition of flooding (due to challenges with sensor accuracy and processing and interpretation of imagery), and limited geographical coverage. EO-based approaches can also be applied in conjunction with approaches using other types of data and modeling; see Box 1 for the example of the Southeast Asia Disaster Risk Insurance Facility (SEADRIF) parametric insurance product.

Applications of Flood Risk Modeling to CDRF

Flood risk modeling is a critical tool to inform flood-related climate and disaster risk finance, from initial diagnostics to the development and implementation of CDRF instruments (see Note 1). The purpose of the modeling will influence the choice of approach, particularly for the exposure and vulnerability modules (e.g., modeling damage to buildings versus impacts to crops versus people affected).

In the development of flood risk transfer instruments (e.g., sovereign flood insurance), flood risk modeling is required to inform the pricing and underwriting of instruments by the market. Insurers may use flood risk modeling to inform risk-based pricing; see Box 2 for the example of the Nepal flood model. They may also use modeling to monitor potential accumulations, determine how much capital they may need to hold, and inform reinsurance purchasing decisions. In the case of CDRF instruments that utilize parametric indexes for triggering, flood models are also sometimes used in the near-real-time trigger systems; see Box 1 for the example of the SEADRIF parametric insurance product.

Box 1.
Risk modeling and parametric index used for SEADRIF product in the Lao People's Democratic Republic

The SEADRIF (Southeast Asia Disaster Risk Insurance Facility) sovereign flood insurance product in Lao PDR uses a parametric index based on a combination of daily hydrological modeling of flood extent, estimates of flood extent derived from satellite data, and gauge data. The product covers multiple types of flooding, including fluvial (river), pluvial (surface water), coastal, and tidal flooding. The parametric index used to determine payouts under the insurance policy is based on the estimated number of people affected. A stepped parametric trigger structure is used, with different payment levels for moderate and severe events.

An operational flood monitoring tool was developed to monitor flood events and assess whether a flood event has triggered the insurance policy. The tool combines a range of data sources, as described below and shown in Figure 2.

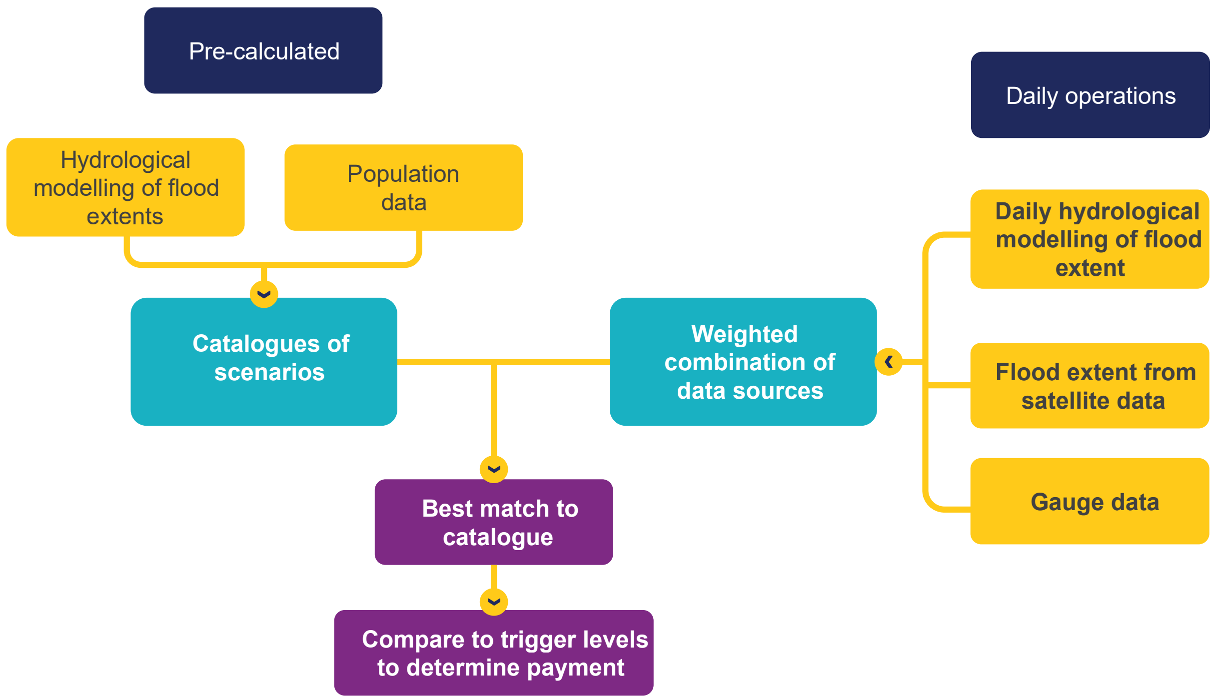
A weighted combination of near-real-time data sources:

- Flood extent footprints derived from Sentinel-1 satellite data from the European SpaceAgenc
- Real-time local river and coastal gauge measurements (e.g., water level)
- Simulations from daily hydrological modeling of flood extent

Catalogs of pre-computed scenarios:

- A catalog of pre-simulated modeled flood depth maps, from which the tool selects the most representative map for the event for individual subareas and types of flooding, based on the available gauge data, simulations, and satellite data described above
- Gridded population maps, which are overlaid flood maps to estimate the total number of people affected for each of the scenarios

Figure 2: Overview of data and models used for SEADRIF parametric flood insurance



Source: Karen Whittingham, "Building Financial Resilience to Flood Risk in South-East Asia," October 24, 2023, JBA Risk Management, https://www.jbarisk.com/products-services/consultancy/our-work-around-the-world/building-financial-resilience-to-flood-risk-in-south-east-asia/.

SEADRIF also developed a stochastic model to enable modeling of the risk profile, which provided the information necessary for pricing the product. The model was compared with historical events to ensure that it properly represented and aligned with the data used for the parametric index.

Box 2.
Flood model for insurance applications in Nepal

Context and rationale: Nepal is highly prone to flood hazards due to its monsoonal climate and rugged topography. Over the last 10 years, Nepal has been struck by multiple lower-severity flood events; the 2017 floods affected approximately half of the country. A key focus of the World Bank's support to the Government of Nepal is improving the data and analytics available for understanding and assessing natural catastrophe risk, including the risk of flood, which must be addressed by the government's efforts to build climate resilience.

Responding to the limitations in the historical record and the impacts of climate change, the World Bank worked with its partners, including Aon Impact Forecasting, to develop a state-of-the-art flood catastrophe risk model for Nepal, using as much local data as possible. This model will enable the World Bank to provide the Government of Nepal with recommendations for improving the financial resilience of its public assets as well as options for implementing risk-informed pricing supported by the insurance regulator.

Methodology: The Nepal flood model was developed using local data and high-resolution modeling at 30 m and calibrated with Nepal Department of Hydrology and Meteorology data from hundreds of streamflow rainfall stations. It covers flooding from rivers as well as surface water and flash floods, and it calculates the cost of damage to physical assets, including residential, commercial, industrial, and infrastructure assets.

Vulnerability functions were developed from a combination of component-based engineering approaches, damage data, and engineering surveys collected post-disaster in Nepal. Over 15 property risk classes are supported, and vulnerability is differentiated by attributes such as construction material, height of building, and (particularly important for flood losses) the presence of a basement.

Before the Nepal flood model was finalized, an extensive validation exercise was conducted; this compared the model's flow analysis to historical data, its flood hazard maps to maps from other sources, and its output to satellite-based observations (for example after the September 2024 floods). The model includes a comprehensive model for current climate conditions, and it also generates additional stochastic event sets for a range of future climate change scenarios.

FAQs

Can Earth observation replace flood modeling?

Currently, the historical EO data are insufficient to assess the risk of all possible events. However, as this time series grows, the data become more valuable for developing risk profiles for smaller and more frequent events, where models are traditionally weaker. Some 20–30 years of data can provide sufficient relevant information.

EO data currently show more potential in rural areas, where the built environment interferes less with the images picked up by satellites. Some recent promising approaches using Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data have been trialed along river basins in Bangladesh and Argentina, and policies are now being placed in the market based solely on EO approaches—particularly in data-scarce regions such as Africa.

What is possible if no local data can be obtained?

Global flood models have enabled catchments with even very minimal data to be modeled—assuming that the catchments can be compared with other catchments globally for which more data are available. If a suitably similar catchment exists, then information from this catchment can be utilized to model the catchment with no data. While this is not an ideal approach, it can at least provide an initial representation of flood risk and potential losses. Users should be aware, however, that these models have not necessarily been validated locally for all countries.

What is the most important information needed when developing a flood risk model?

Although many sources of data are required to build a reliable flood model, several data sets are particularly important:

Elevation data:

The digital terrain models (DTMs) and digital elevation models (DEMs) that represent elevation data are highly important, as variations in the elevation of the ground over short distances can greatly influence flood depth and location. Where available, bare-earth DEMs should be used. LiDAR data provide the highest degree of accuracy, but they are often not available for developing countries; in such cases satellite-based DEMs (e.g., Copernicus GLO-30) should be used.

Flood protection:

Flood defenses and drainage systems can direct and limit flooding within the modeled domain, in particular in urban areas. Representing flood protection in any modeling can be difficult because information on the location of each protection/drainage network, and the standard of protection it provides, is limited. Often broad and generalized assumptions are made to estimate the defended area and level of protection against fluvial flooding. Attempts have been made to catalog standards of flood protection; the most significant to date is FLOPROS.[4]

Historical observations:

Observations—for example, from precipitation and streamflow gauges—are key for developing realistic models. In developing countries, observations are often incomplete, inaccurate, or available only over a short time, and therefore don't capture extreme events.

[4] Paolo Scussolini et al., "FLOPROS: An Evolving Global Database of Flood Protection Standards," Natural Hazards and Earth System Sciences 16 (2016), https://doi.org/10.5194/nhess-16-1049-2016.

Vulnerability functions:

These are less commonly available for flooding than for other perils. In both developed and developing contexts, the quality of historical data is limited. Some models use data based on global or regional experience and evidence, such as JRC data[5] or US Federal Emergency Management Agency (FEMA) HAZUS vulnerability curves. However, applying these to a particular country adds uncertainty. Ideally, additional local research—for example, on local building characteristics—should be used to understand better the relationship between flood depth and damage.

How do I know if I can trust a flood risk model?

While flood risk models have high degrees of potential bias and uncertainty due to the complexity of the peril being modeled, they are still representations of the physical world and can therefore be tested at various levels to ensure they provide trustworthy risk metrics. Any model needs to be calibrated and validated against historical data, a process that can be particularly complicated in emerging market and developing economies (EMDEs), which often lack needed historical data.

Where data are available, the model should be validated at both the individual-component level (for example, by comparing modeled and historical data for precipitation/river discharge, inundation depth, etc.) and at the output level (for example, by comparing population affected in historical events to population estimated by the model).

Reading List

Norris, Alastair, Stuart Fraser, Michaela Mei Dolk, and Olivier Mahul. 2023. “Flood Risk Modeling to Support Risk Transfer: Challenges and Opportunities in Data-Scarce Contexts.” World Bank. https://documents.worldbank.org/pt/publication/documents-reports/documentdetail/099255511072316127/idu01dab70bb0f83b04d830b5460a05f6c3f5775.

[5] J. Huizinga et al., Global Flood Depth-Damage Functions: Methodology and the Database with Guidelines, EUR 28552 EN (Publications Office of the European Union, 2017), doi:10.2760/16510.