# Hazard Specific Risk Assessment: Hydrological

## 1 - Flood Hazard and Risk Assessment

*Key words: floods, flood hazard map, historic flood risk assessment, preliminary flood risk assessment (PFRA), flood risk assessment (FRA)*

### Description of the Hazard, Sources and Setting

Water is a resource before being a threat. That is why it would be of little use to consider flood risk assessment by itself without casting it in the framework of Flood risk management and water management at large. Any measure undertaken to reduce flood risk has an effect on other segments of water use (e.g. potable water, industrial use and irrigation, recreation, energy production) and many of them modify flood risk in different geographical areas being the river network a unique connected system.

As for other risks, flood risk can be analysed through the lenses of the three main terms of the risk equation: hazard, vulnerability, exposure and capacity. In comparison to other risk, flood suffers of a very strong unbalance between the level of maturity in assessing the different elements: while hazard modelling is well advanced, among other factors due to the relatively high predictability of floods, exposure characterisation and vulnerability analysis are under developed when compared to other perils (e.g. seismic). This section will give some highlights on the most developed practices for flood risk assessment without entering details on the specific methodologies, but it will stress the aspects that are pertinent to floods specifically, and try to clarify the states of research and practice in FRA in relation to different uses of flood hazard and risk information. Matters that are discussed here include the issue of scale, the challenge in capturing flood correlation on large scale events, the necessity of considering Climate Change, the strong links with other perils determining complex multi-hazard scenarios.

Flooding occurs most commonly from heavy rainfall when natural watercourses do not have the capacity to convey excess water. However, floods are not always caused by heavy rainfall. They can result from other phenomena, particularly in coastal areas where inundation can be caused by a storm surge associated with a tropical cyclone, a tsunami or a high tide coinciding with higher than normal river levels. Dam failure, triggered for example by an earthquake, will result in flooding of the downstream area, even in dry weather conditions. A variety of climatic and non-climatic processes influence flood processes, resulting in different types of floods: riverine floods, flash floods, urban floods, glacial lake outburst floods, coastal floods.

As a result, Floods are the natural hazard with the highest frequency and the wider geographical distribution worldwide. Although, the majority of floods are small events, monster floods are not infrequent. Examples are easy to find even in recent years:

In 2010, approximately one fifth of Pakistan territory was flooded affecting 20 million people and claiming close to 2000 lives. The economic losses were estimated to be around 43 billion US dollars. One year later another monster flood stroke South East Asia. The flood event extended across several countries and a few separate limited flood events parts of the same nations: Thailand Cambodia and Myanmar



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and heavy flooding in Vietnam. Meanwhile, Laos also sustained flood damage. The death toll in this case reached close to 3000. Considering only Thailand in terms of economic losses this flood ranks as the world's fourth costliest disaster as of 2011[1] surpassed only by the 2011 earthquake and tsunami in Japan, 1995 Kobe earthquake, and Hurricane Katrina in 2005.

Not only Asia is stroke by large scale events. Worth to mention are the 2014 floods in South East Europe that killed 80 people and caused over 3.8 billion US Dollars of economic losses, and of course the levee failures in Greater New Orleans in 2005 during Hurricane Katrina, the costliest disaster from natural hazard in US, summing up to about 150 billion US dollar losses.

Flood magnitude depends on precipitation intensity, volume, timing and phase, from the antecedent conditions of rivers and the drainage basins (frozen or not or saturated soil moisture or unsaturated) and status. A number of climatological parameters that are likely to be affected by climate change are: precipitation; wind storms; storm surges; sea level rise.

On average, there is consensus that extremes are likely to increase in the majority of the locations on earth; this fact, combined with land use changes mainly towards soil consumptions and the tendency to urbanization, tends to exacerbate the effects of extremes, flooding making no exception to this.

For this reason, climate change has a prominent role when assessing flood risk as it is captured in many legal documents and directives. However, the uncertainty connected to the climate change impacts on flood hazard and vulnerability limits sometimes the possibility of evaluation adaptation measures according to classical methodologies such as cost benefit analysis. Because of that, it is suggested to tackle the problem by adopting as much as possible the following guidelines. First is to base the risk assessment studies on a large enough climate change scenario ensemble in order to capture as much as possible the uncertainty associated with such evaluations. Second is to choose robust strategies of adaptation rather that aiming at optimal ones focusing on the ones that meet the chosen improvement criteria across a broad range of plausible futures. Third is to increase the robustness of the adaptation process by choosing "adaptive" strategies that can be modified as the future scenarios unfold. This last point should be supported by designing a proper exploration of the multiplicity of plausible futures.

Including climate change in a scientifically sound way in Flood Risk Assessment and Management remains a challenge. The basic concepts that represent the basis of decision making now are sometimes invalidated. As an example, the widely-used concept of "return period", at the basis of flood protection design targets, needs to be rethought in a non-stationary context as the one put forward by climate change. Therefore, new approaches have to be developed to be able to quantify the risks.

In the stationary case, there is a one-to-one relationship between the m-year return level and m-year return period which is defined implicitly as the reciprocal of the probability of an exceedance in any one year. Return periods were assumedly created for the purpose of interpretation: a 100-year event may be more interpretable by the general public than a 0.01 probability of occurrence in any particular year.

Under non-stationary conditions the above definition does not hold and another angle should be proposed. Possibilities are to communicate the return periods as expected waiting time for a certain threshold starting from a certain year, in this case we define the *m*-year return level as the level which the expected waiting time until an exceedance of a threshold occurs is *m* years and we can account for non-stationarity. Similarly, we can define an *m*-year return period given is that the expected number of events in *m* years is one. This concept can be extended easily to a non-stationary case, considering a specific time window.

## Hazard assessment

The sudden changes of the inundation maps and flood hazard maps is a distinctive feature that influences flood hazard assessment. This implies that different methodologies are needed to define flood hazard when different scales are considered.

The implementation of very detailed inundation models is often very expensive: data hungry and calibration intensive. That is why it is most often flood hazard and risk assessment exercises are broken down into two stages: a preliminary Flood Risk Assessment (PFRA)[2] and a final, more detailed, Flood Risk Assessment (FRA).

The PRFA is extensive geographically and in terms of flooding mechanisms (i.e. different types of floods) considered, while it uses approximated approaches to hazard and many times neglects vulnerability. PFRA has the objective of defining priority areas for further characterization with advanced models using detailed information about topography (Digital Elevation Models-DEMs), break lines, and flood defences. In this way resources are invested where risk is higher maximizing the return in investment in detailed assessment in areas where high social and economic value are threatened. Attention should be paid also to areas of potential new development that might not appear as priorities in the PFRA from exposure and existing risk point of view.

PFRA is related to areas where potential significant flood risks exist or are probable in the future. Such areas are identified as Areas of Potentially Significant Flood Risk (APSFR) in the preliminary flood risk assessment. If in a particular river basin, sub-basin or stretch of coastline no potential significant flood risk exists or is reasonably foreseeable in the future, no further action would have to be taken.
If APFSR are identified, then a full detailed Flood Hazard and Risk Assessment (FHA & FRM) shall be undertaken.

As in the case of all natural and technological hazard, and both in the case of PFRA and the full FRA, the hazard assessment needs to physically and statistically model the Initiation Event (i.e. the trigger, in this case many time the trigger is Rainfall)[3] and after that to model the run-out/evolution of that event. In the case of fluvial flooding hazard, the run-out is modelled using a hydrological model to properly assess the routing of precipitation from rainfall to runoff and a hydraulic model to evaluate in detail the spatial extensions of floodable areas.

After the flood hazard assessment is completed a proper risk assessment should be conducted. Flood Risk Assessment should quantitatively assess the potential adverse consequences associated to flood scenarios and should consider impacts on the inhabitants potentially affected, the relevant economic activity of the area potentially affected and on all relevant risk receptors. The definition of risk receptors is also a political decision and a discussion phase with relevant governmental bodies and stakeholders should be made. In both the PFRA and FRA a combination of the following approaches should be used when possible:

- Historic Flood Risk Assessment: information on floods that have happened in the past both from Natural Sources of Flood Risk and Floods from infrastructure failure.
- a Predictive Analysis assessing the areas that could be prone to flooding, as determined by predictive techniques such as modelling, analysis or other calculations, and of the potential damage that could be caused by such flooding.
- Expert opinions especially of departments and agencies to identify areas prone to flooding and the potential consequences that could arise both as a validation step and as a complementary information for the predictive analysis.

In case of flood risk, this type of approach connects to the planning phase that informs prevalently the land use planning in order to not create new flood risk by locating new assets in flood prone zones and if possible reduce the current level of risk by strategies for modifying the land use or developing appropriate flood protections. Therefore, the main tools in this case are represented by the hazard maps and risk maps are intended as a simple overlay of hazard maps and exposure in order to identify the exposed elements on which to intervene; while a full Probabilistic approach, based on the development of a full scenarios set is often neglected, as discussed in the following chapter.

The outputs of probabilistic quantitative risk approaches are the probability of occurrence of certain loss levels usually presented as risk curves plotting expected losses against the probability of occurrence for each hazard type individually, and expressing also the uncertainty, by representing a probability distribution at each point of the curve in many cases drawn as confidence interval at a certain significance level or generating at least two loss curves expressing the minimum and maximum losses for each return period of triggering events, and associated annual probability. The risk curves can be made for different reference asset units, e.g. administrative units such as individual slopes, road sections, census tracts, settlements, municipalities, regions, provinces or a country.

While for some hazards (e.g. seismic hazard) quantitative approaches to risk assessment are frequently fully probabilistic in nature that is not always the case for Floods. Many times, the approach to flood assesses the geographical distribution of the severity of loss due to the occurrence of a postulated event (i.e., Scenario) or based on a Hazard map with assigned frequency, which does not take into consideration spatial correlation within a catchment or among different catchments.

Source events are nonhomogeneous in space and non-stationary in time, and the probability of a source event is a complex function of both location and time. For rainstorms, in any given year, the probability of a source event depends on spatial differences in topography and atmospheric circulation patterns that change relatively slowly with time (here, atmospheric circulation patterns refer to average annual climatic conditions, not day-to-day variability).

Amongst all source events, rainfall probabilities are among the most difficult to model because of the unlimited scope of potential source events that must be considered when evaluating flood hazards. Every rainstorm has a different temporal and spatial signature that defies classification, even if classification attempts can be found in literature[4]. Even an objective definition of an event, especially when large spatial domains are considered, magnitude is still a debated research topic that hampers the definition of proper Magnitude-frequency relationship constraining scientist to less efficient scenarios simulation methodologies. Eventually, the very expensive modelling of the flooding process causes sometimes the impossibility of using methodologies (e.g. logic trees) for uncertainty estimation and propagation that are widely used in other "hazard" communities. All those reasons make Probabilistic risk assessment a challenge in case of floods.

Nevertheless, the management of flood risks is based on a judicious combination of measures that address risk reduction, retention and transfer through a strategic mix of structural and non-structural measures for preparedness, response and recovery. Decisions have to be made on how to share the cost of taking risk placed on society among governments (central, regional and local governments), interested parties (such as private companies), communities and individuals. This is even more true if we consider that vicinity to water is an advantage for all main human activities (e.g. Urban development, transport, energy production, entertainment) and coastal and flood-plain areas are valuable assets in this sense. Therefore, a full quantitative assessment based on a fully probabilistic approach is essential to properly meet the Flood Risk Management objectives.

**TABLE 1** - List of some of the key basic datasets to perform the flood hazard assessment

| Description of Input Data | The national entities that most commonly have this data | Examples of Existing open databases available from international sources |
|---|---|---|
| DTM | National Cartographic Institute | SRTM Global DEM, ASTER G-DEM |
| Land Cover/ Land use | National Cartographic Institute | Global Land Cover from different organizations (NASA, FAO), GlobCover from Envisat/Meris, MODIS GlobCover |
| River hydrography | National Cartographic Institute | Hydrosheds |
| Rainfall Data | National Hydro-Meteorological services | gauge data sets (e.g. CRU TS, GPCC, APHRODITE, PREC/L), satellite-only data sets (e.g. CHOMPS) and merged satellite-gauge products (e.g. GPCP, CMAP, TRMM 3B42) |
| Streamflow Data | National Hydro-Meteorological services | Global Runoff Data Centre (GRDC) |
| Geologic/pedologic/soil parameters | National Cartographic Institute | Harmonized World Soil Database |
| Dams | National Dam Regulation body | Global Reservoir and Dam Database |

## Exposure and vulnerability

In order to proper evaluate flood impact and all quantitative indicators that are the final product of a probabilistic risk assessment vulnerability represents a crucial step. So far, in flood risk assessment, this is probably the main weak link. Convincing methodologies to evaluate social vulnerability to floods exist[5] and can be considered up to the reliability level that is expressed in the case of other hazards. When a more quantitative vulnerability assessment is needed, that involves the evaluation as a first step of the physical damage trough a vulnerability or fragility curve or table, the level of accuracy and portability in case of floods is still a challenge for different reasons. In the case of seismic risk, the loss quantification is driven by the necessity of evaluating residual risk in the aftermath of an event to quantify displaced people that need to be managed. This results in a more organized and refined loss data collection. In the case of floods, structural safety is less of a concern and the loss data gathering is less structured, resulting in heterogeneous datasets that could hardly be used to derive empirical vulnerability curves. Additionally, in case of floods a large part of the loss is due to the damaged content which increases the data variability, hampering the application of regression methods to derive vulnerability curves directly from data. Physical modelling of vulnerability to floods is based on isolated attempts due to high cost of this approach that is not compensated by other applications as in the case of other perils (e.g. for seismic for the evaluation of retrofitting strategies).

Expert judgement remains the most diffuse approach. However, flood vulnerability is affected by numerous factors such as settlements conditions, infrastructure, authority's policy and capacities, social inequities, economic patterns and sometimes expert judgement is not able to capture all these aspects.

A competent mix of expert judgement verified by field data seems the most robust methodology to derive quantitative vulnerability curves.

Strong cooperation with other perils would be beneficial to the progress in this field. The vulnerability assessment is closely related with the ability to characterize properly the exposed elements to floods. The exposure characterisation is another field where cooperation in a multi-hazard framework would be beneficial for different reasons. Although some exposure characteristics are functional to the flood vulnerability assessment only (e.g. the height of the entrances with respect to the street level) the majority of them are common and could be collected in a joint effort when performing a full disaster risk assessment study. In order to make this process efficient a proper standardization would be needed starting from the taxonomy till the IT formats to describe the assets.

**TABLE 2** - Some of the key attributes to be collected for exposure are listed

| Exposure Data Class | Parameter to be collected relevant to FRA |
|---|---|
| buildings | monetary value |
| buildings | type of construction |
| buildings | building height |
| buildings | ground floor use |
| buildings | main occupancy |
| critical infrastructures | critical facilities |
| critical infrastructures | line infrastructures |
| population | population distribution |
| population | age distribution |
| population | gender distribution |
| land use | predominant land use type |
| land use | monetary value per $m^2$/ha/$km^2$ |
| economy | workplaces |
| economy | GDP |
| economy | income distribution |

### Risk assessment and use in National DRR measures

It is not by chance that Floods are the most frequent and damaging in terms of cumulate and Annual Expected Loss (AEL) worldwide. In fact, people tend to gather close to rivers, lakes or concentrate in the coastal areas because water is a resource before being a threat: this determines a high concentration of assets, and therefore a high level of risk, in flood prone areas, and this tendency will likely increase in future. It is for this reason that flood risk assessment needs to be closely linked to flood management or even integrated flood management were the goal is to maximize the net benefit from the use of flood plains, rather than trying to fully control floods. In this sense, it is necessary to put forward the concept of integrated flood management as promoted by the World Meteorological Organization (WMO) that manages flood risk through the application of risk management principles such as:

- Adopting a best mix of strategies;
- Reducing vulnerability, exposure and risks;
- Managing the water cycle as a whole by considering all floods, including both extremes;
- Ensuring a participatory approach;
- Integrating land and water management, as both have impacts on flood magnitudes and flood risks;
- Adopting integrated hazard management approaches (including risks due to all related hazards such as landslides, mudflows, avalanches, storm surges), and creating synergies.

The last point tides into one of the other peculiarity of flood risk that is the strong correlation with other perils that are either triggered by the same event or that materialise as a cascading effect either downstream or upstream the flood event. A complete flood risk assessment should take into consideration those aspects at least in a worst-case scenario approach.

Floods are in essence a multi-hazard phenomenon as their trigger (e.g. storm) frequently brings along compound effects (e.g., combined riverine flood and storm surge in coastal areas), coupled effects (e.g. diffuse landslides during high intensity precipitation events), amplification effects, disposition alteration and cascading effects. It would be an incomplete risk assessment if those conditions are not taken into account at least in a qualitative way.

However, despite the growing demand for multi-hazard risk assessment capabilities worldwide, and the many global initiatives and networks that develop and deliver natural hazard and risk information, the focus of global initiatives to date has been mainly on hazards and in individual hazard domains. Moreover, while existing global initiatives recognize the importance of partnerships with local experts, connecting hazard and risk information from local to global scales remains a major challenge.

Even if science may not be ready to perform a scientifically sound an exhaustive multi-hazard risk assessment in fully probabilistic terms, it would be incautious to take decisions without considering at least a set of “reasonable” worst case scenarios able to capture the multi-hazard essence of the environment analysed. It is therefore suggested to start from a multi-hazard risk identification process to identify how the complexity of the territorial system interacts with multiple causes. This analysis starts, but it is not limited to, a deep historical analysis by means of conventional and unconventional sources of information. From there, the expert performing the analysis should select the most appropriate scenarios and characterize them in terms of impacts their likelihood and uncertainty. This would represent a fundamental part of the risk assessment determining coping capacity and resilience of the system analysed.

## A case of a country good practice

### FEMA flood hazard maps, and the National Insurance Flood Program (NFIP)

The Federal Emergency Management Agency (FEMA) in the United States is the responsible government agency to develop and disseminate flood hazard maps, also known as Flood Insurance Rate Maps (FIRM). The need to develop (or update) a FEMA flood maps for a particular area in the US is born through collaboration between local, state, and federal government officials. A watershed is identified given the need, the available data, and the regional knowledge. The map is then developed utilizing the best available data, and the scientific modelling approach that these data can support. The accuracy of the outcome map depends on what kind of data and methods were used to develop it. The FEMA maps depict flood zones, ranging from high to low hazard. The source of flooding can be pluvial (induced by precipitation), fluvial (riverine), or storm surge. The maps are traditionally distributed in (~3.5 mi2) panels; but currently, they can also be viewed seamlessly through an interactive GIS portal.

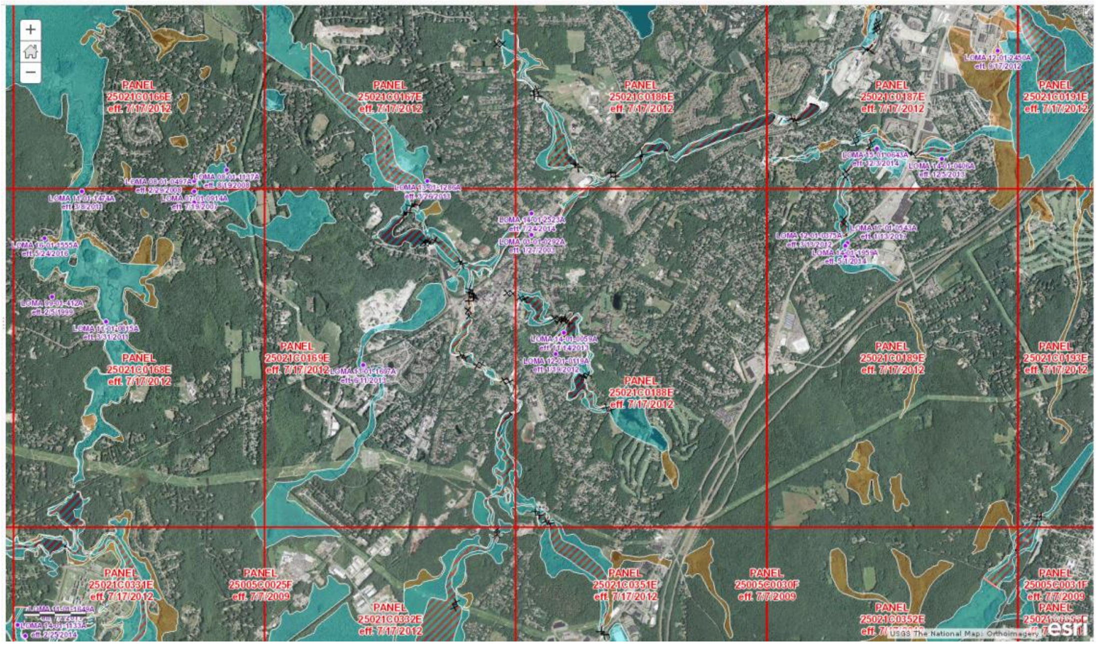

**Figure 1** - GIS viewer showing the FEMA's National Flood Hazard Layer (Official)

The map panels, associated Flood Insurance Study (FIS) reports, data sheets, and letters of modification can all be downloaded by anyone (https://msc.fema.gov/portal/availabilitySearch). The FIRM maps are under an ongoing cycle of revision and update due to the increasing availability of related information, whether it is scientific data, or new events that change the assumed probability structures.

The FIRM maps can be used for residential, and commercial or industrial insurance programs alike. For residential insurance, the NFIP was created to enable property owners in participating communities to purchase insurance protection, administered by the government, against flood losses. The program requires flood insurance for all

loans or lines of credit that are secured by existing buildings, manufactured homes, or buildings under construction, that are located in a community that participates in the NFIP. FEMA which administers the NFIP publishes information and statistics to the public through the official NFIP website:
https://www.floodsmart.gov/floodsmart/.

## Malawi flood hazard risk profile

The Africa region shows a continuously increasing level of risk materializing through natural hazard extremes. These natural risks are a hurdle to the development of many African countries that see GDP and investments impaired by the impact of such natural hazards. This is particularly true for Malawi that is periodically hit by severe floods like the one occurred in the first part of 2015 when the Shire River south of Lake Malawi and tributaries flooded large parts of the country in several flood waves. More than 170 people lost their lives, thousands were displaced and crops were lost. In order to increase scientific-supported awareness of risk at the national level and sub-country level GFDRR with EU ACP funds has financed the production of hazard flood maps which to form the basis for a preliminary risk assessment work producing risk figures. The final purpose of that being engaging with the governments in a risk financing program for Malawi. Risk financing could play a key role in protecting the financial investments and can lead the way to a future where such risk is understood, reduced and controlled.

The study was conducted at country level using the TANDEM-X 12.5m resolution global DEM therefore producing maps with a very fine resolution considering the overall extension of the study. Such maps are then used to compute in a full probabilistic manner economic parameters such as Annual Average Loss caused by floods broken down into different categories of assets, residential, commercial, industrial buildings, agriculture, critical assets and infrastructures; as well as impact on population and GDP. All this analysis in both present and climate change conditions. Although the country level scope frames this study as a preliminary flood risk assessment the nature of the parameters computed enables an informed dialogue with the national authorities to plan necessary mitigation measures including further studies in the hotspots highlighted by the study.

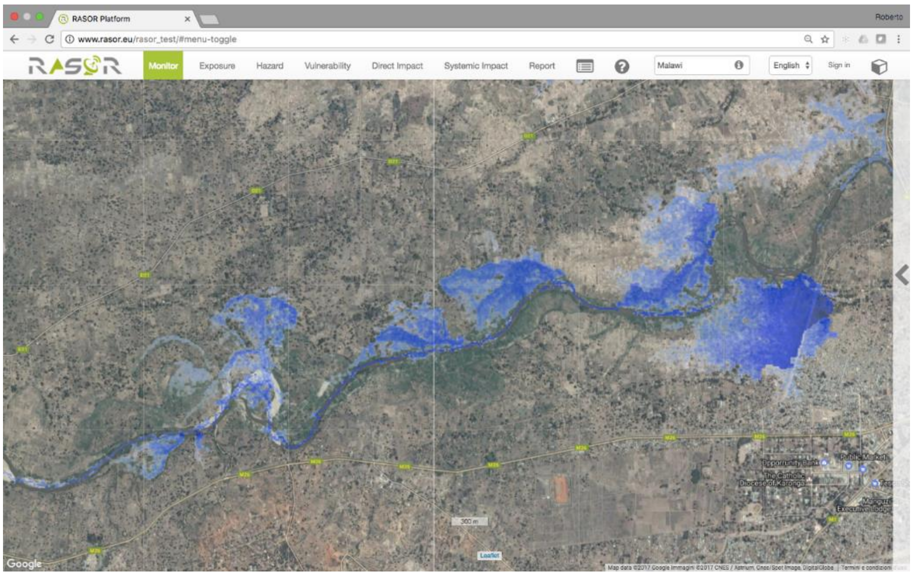


**Figure 1** - 100-year flood map depicting maximum water depth for the river flowing into Karonga city in Malawi

## Resources for further information

- International community of practice focused on this hazard
  - Preventionweb.org
  - Gfdrr.org
  - UR
- Other substantial peer-reviewed guidelines from reputable institutions
  - APFM tools
- Open source hazard and risk modeling tools
  - Think hazard
  - GAR
  - RASOR
  - World Bank Caribbean Risk Information Programme
  - Aqueduct Global Flood Analyzer
  - GloFAS
  - GFMS
  - Dartmouth Flood Observatory
  - OpenStreetMap
  - InaSAFE
  - Global Assessment Report Risk Data Platform
- Successful and well documented national hazard and risk assessment with results used in DRR
  - UK
  - The Netherlands

*Authors: Roberto Rudari (CIMA Foundation)*
*Contributors and Peer Reviewers: Yasir Kaheil (FMGlobal), Paolo Scussolini (Vrije Universiteit Amsterdam)*

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[1] From Word Bank estimates

[2] (A Communication on Flood risk management; Flood prevention, protection and mitigation at link http://ec.europa.eu/environment/water/flood_risk/com.htm)

[3] Many other trigger for flooding exist, e.g. sudden outbursts from glaciers (ephemeral lakes), collapses of hydraulic structures such as dams or levees, surges caused by wind, tides.

[4] Pinto, J. G., S. Ulbrich, A. Parodi, R. Rudari, G. Boni, and U. Ulbrich (2013), Identification and ranking of extraordinary rainfall events over Northwest Italy: The role of Atlantic moisture, J. Geophys. Res. Atmos., 118, doi:10.1002/jgrd.50179

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