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FLOOD MAPPING

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The **Associated Programme on Flood Management** (APFM) is a joint initiative of the World Meteorological Organization (WMO) and the Global Water Partnership (GWP).

It promotes the concept of Integrated Flood Management (IFM) as a new approach to flood management. The programme is financially supported by the governments of Japan, Switzerland and Germany.

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To the reader

This publication is part of the *"Flood Management Tools Series"* being compiled by the Associated Programme on Flood Management. The *Flood Mapping* Tool is based on available literature, and draws findings from relevant works wherever possible.

This Tool addresses the needs of practitioners and allows them to easily access relevant guidance materials. The Tool is considered as a resource guide/material for practitioners and not an academic paper. References used are mostly available on the Internet and hyperlinks are provided in the *References* section.

This Tool is a *"living document"* and will be updated based on sharing of experiences with its readers. The Associated Programme on Flood Management encourages disaster managers and related experts engaged in the development of risk maps with regard to floods and other hazards around the globe to participate in the enrichment of the Tool. For this purpose, **comments and other inputs are cordially invited**. Authorship and contributions would be appropriately acknowledged. Please kindly submit your inputs to the following email address: apfm@wmo.int under Subject: *"Flood Mapping"*.

ACKNOWLEDGEMENTS

This tool has been prepared as a team effort and makes use of the works of many organizations and experts from various fields of hazard mapping, remote sensing, as well as hydrology and engineering. It has been jointly developed in close cooperation with the APFM Technical Support Unit. The present tool is one outcome of efforts on developing a comprehensive guideline on flood assessment and mapping.

The development of a comprehensive guideline on flood assessment and mapping has been under the leadership of Prof. Erik Pasche (1955-2010), Technical University Hamburg-Harburg, Germany and Roberto Loat, Federal Office for the Environment, Switzerland; the APFM Technical Support Unit guided the process. The APFM highly acknowledges their leadership and dedicated work.

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1 FLOOD MAPPING: WHY AND WHAT FOR?

1.1 Background

1 Maps showing flood hazards, flood-prone areas and related spatial information are indispensable components for an effective approach to Integrated Flood Management (IFM); this is particularly important when discussing spatial issues like land-use planning in the framework of flood management (WMO, 2008b). Moreover, recent major flood events in developed as well as developing countries (Pakistan 2010, Australia 2010/11, China, Thailand and Laos 2011, Nigeria and United Kingdom 2012) urgently call for thorough flood risk assessments in urban and rural settings. While detailed technical methodologies for calculating, modelling and mapping flood prone areas and flood risks are available in data-rich situations[1], the guidance on overall approaches to flood mapping and risk assessments are conspicuously missing, particularly in data-sparse conditions. There is particular need for addressing such situations in developing countries with limited know-how, lack of resources, and inadequate data availability. The situation is even more complicated in transboundary basins due to the absence of acceptable common methodologies for risk assessments and management practices.

2 Flood maps help to visualise results from flood assessments. As such flood assessment and flood mapping are two closely interrelated processes; at a closer view flood mapping incorporates both, preliminary and detailed flood assessments. Flood maps exist in many formats and are highly variable. The development of such assessments and mapping exercises is a complex, multi-disciplinary process involving technical expertise as well as human and financial resources. Presently there are few publications available that provide guidance to develop a program on flood mapping and flood risk assessment. Recently, experience and good

[1] The RiskMap initiative by FEMA uses such detailed technical methodologies and is built up in data-rich environments. Find further information in (FEMA, 2009b) and (WMO, 2010).

practices have been collected in the European Union under the initiative "European Exchange Circle on Flood Mapping" (EXCIMAP, 2007a).

Figure 1 — Flooded area (mud flow) and simplified risk map for an Alpine town in Switzerland

1.2 Objectives of this tool

3 Flood maps play an important role in decision-making, planning and implementing flood management options. The overall goal of flood maps is to provide information on the past and the likely or potential extent of floods and their impacts (sometimes in combination with other related information), which help in making decisions on various aspects of integrated management of floods.

4 Developing flood maps requires a systematic process. It is important to specify the data sets on which the maps will be based and the methodology that will be used. In addition, administrative mechanisms are necessary to develop flood mapping programmes. Based on the above outlined demand for flood information, the objective of this publication is:

> *to provide guidance to undertake flood mapping exercises for the various planning processes on local or national level which cover issues like changing land uses and climate change; land.use regulations and building codes; impacts of urbanisation; emergency response; asset management; flood insurance; or overall public awareness.*

5 In particular the document will:

- Outline the necessary steps and policies to build a framework for flood mapping **(Chapter 2)**
- Explain the process of and products from a flood mapping programme **(Chapter 3)**
- Define data and methodologies to produce flood maps **(Chapter 4)**
- Explain the dissemination of flood mapping products **(Chapter 5)**

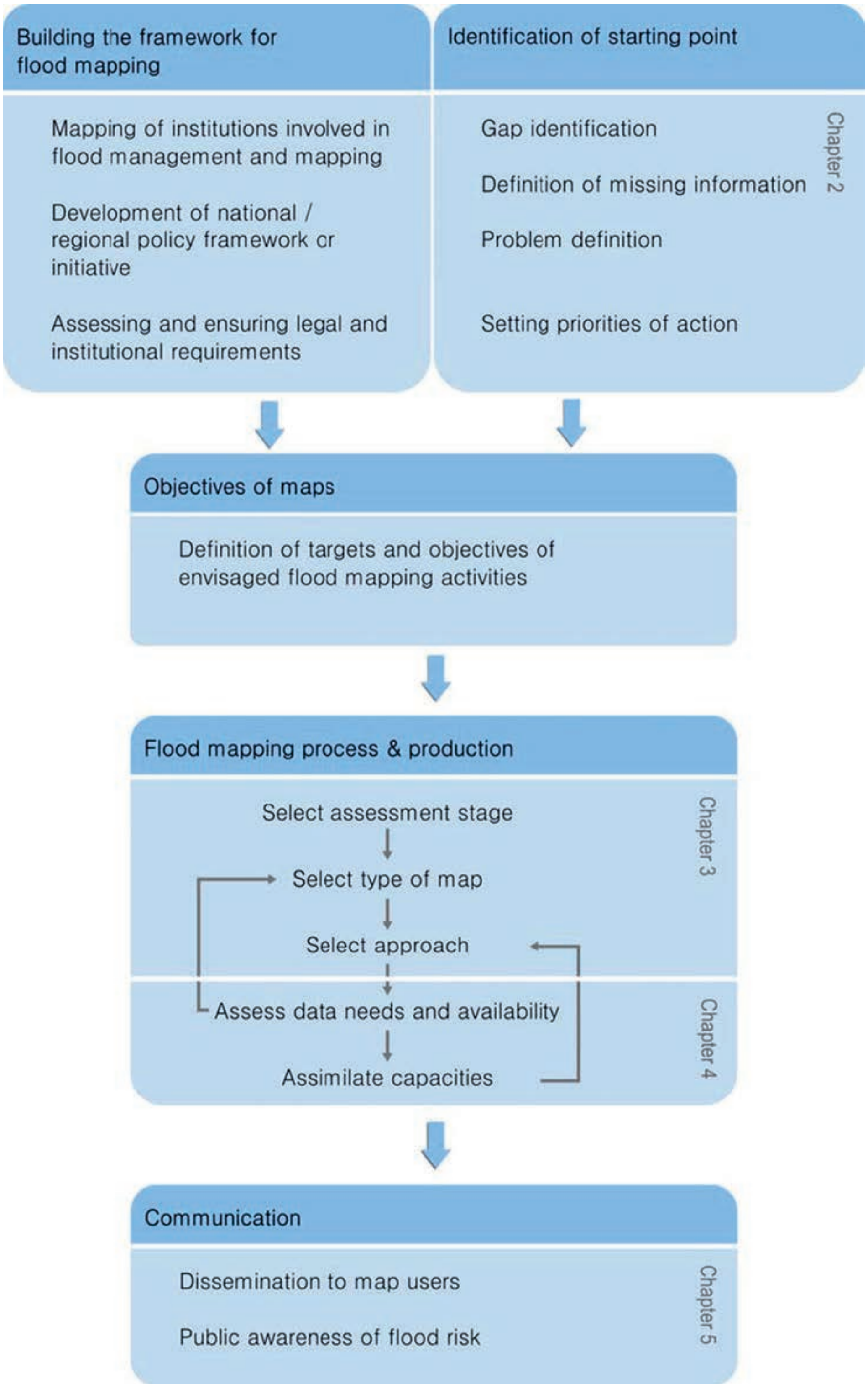


Figure 2 — Steps of flood mapping and document structure

6 This Tool is therefore a complement to a number of other documents in the Associated Programme on Flood Management **(APFM)** Flood Management Tool Series, where flood maps are explicitly demanded, particularly in the field of urban flood risk management (WMO, 2008a), flood emergency management (WMO, 2011a) and others.

1.3 Scope and target readership

7 This tool concerns the assessment and mapping of flooding and floods, where flooding refers to the process and flood can be considered the result of this process. Flooding and floods are addressed in a general way, without giving particular focus on e.g. urban areas or rural settings. In particular, urban flooding would require more detailed basic data (topographic, terrain, socio-economic) and may also require a different set of approaches, especially modelling approaches to address the complex setting with many artificial obstacles in the course of a flood wave (WMO, 2008a).

8 In the mapping process, the following issues are of particular interest:

- Data requirements (such as topography, terrain and hydrological);
- Assessment methodologies;
- Map products.

9 In addition to the technical issues, the administrative aspects of the mapping process are addressed as well.

10 The present document is directed towards a readership which deals with applied flood management; these are flood management practitioners, river planning experts, local and district government officials dealing with water resources, non-governmental organizations (NGOs) (in particular those implementing or advocating for flood management in developing countries) or any other stakeholder that uses flood information represented on flood maps (see **Table 1**). The present document only provides advice to technical personnel who are directly implementing flood risk analysis and developing flood maps.

Table 1 — Main stakeholders and their interest for various flood assessments and corresponding maps

Stakeholder	Interest
Local government	Numerous space-specific decisions Emergency planning / coordination
Flood management agencies	Asset management – targeting investment to manage flood risks; emergency planning
Spatial planning agencies	Development plans: Avoidance of erroneous development in the floodplain through appropriate (building) regulations
Developers	Flood risk awareness
The public at large	Flood risk awareness, insurance premiums / property values, etc.
Disaster management agencies	Emergency preparedness, planning for rescue and relief
Environment agencies	Flood risk and impact on pollution control; the promotion of biodiversity and landscape.
The insurance industry	Data providers, insurers – added value products for calculating premiums, insurability

1.4 The role of flood maps in IFM

11 An IFM approach calls for a paradigm shift from the traditional, fragmented and localized approach, and encourages the use of river basin resources as a whole, employing strategies to maintain or augment the long term productivity of floodplains, while at the same time providing protective measures against losses of life due to flooding (WMO, 2009) – see also **Section 2.1**.

12 Integrated Flood Management requires various specialists to work together under a joint flood management strategy or policy. While the overall aims and objectives of such policy are usually explicitly provided, the consequences for the application of various principles are far less understood. In this context, flood management tools could be described as instruments to facilitate the application of these principles of multi-disciplinary and participatory decision making in their pursuit to provide integrated and sustainable flood management solutions.

13 Putting the IFM into practice requires identification and assessment of present and future risks, creation of policies based on the awareness of such risks and implementation of the policies with due care to avoid new risks from arising and to reduce existing risks. Flood hazard and risk maps (and related products) provide important evidential support to the development of flood management plans and future investment choices (WMO, 2008b). Further, as part of flood emergency response, flood hazard and risk maps provide crucial evidence for decision-making on evacuation and shelter, search and rescue, as well as other flood-reduction activities (WMO, 2011a, 2011b, 2012) such as the APFM Tools on Flood Emergency Management, Management of Sediment-Related Risks, Management of Flash Floods.

2 FRAMEWORK FOR FLOOD MAPPING

2.1 Concept of risk management

14 The assessment and mapping of hazards, risks and capacities is an important step in the management of the respective risks and disasters. This is well-reflected in the widely known risk management cycle[2], which can be represented with four distinct phases:

Phase	Activities
Assessment	Identify and analyse hazards, vulnerability and risk in a particular location and develop the respective maps
Evaluation (weighting)	Consider people's perception of risks and the communities' willingness to reduce risks (to invest for increased safety)
Management	Develop overall concepts and particular risk reduction projects using preventive and preparedness measures
Measuring	Establish monitoring systems and measure effectiveness of risk reduction

Figure 3 — Concept cycle of risk management (Renn, 1992)

15 Mapping is particularly important for the assessment and management phases. Here, flood maps play a pivotal role in representing flood information and management options in the geographical context. A similar approach is used by FEMA in their RiskMAP programme (see **Chapter 5**).

2 The International Risk Governance Council **(IRGC)** helps to improve the understanding and governance of systemic risks that have impacts on human health and safety, on the environment, on the economy and on society at large. Find further information in (IRGC 2006).

2.2 2.2 Policy frameworks and initiatives

16 A dramatic increase in flood (and other disaster) losses has been observed over the past decades; developing countries are particularly affected from this increase. The Hyogo Framework for Action – Building the Resilience of Communities and Nations, 2005-2015 (UNISDR, 2005) is a global response to that trend. This internationally agreed-upon framework defines five priorities for disaster risk reduction with specific measures for all levels and in the relevant sectors. The 2nd priority for action directly calls for the identification, assessment and monitoring of risks. Hazard and risk maps are seen as important documents for decision-making as well as for communities at risk. A key activity under priority 2 is to *"develop, update periodically and widely disseminate risk maps and related information to decision-makers, the general public and communities at risk in an appropriate format"*.

17 The IFM approach serves as an important framework and sets particular priorities, especially for the management of flood risks. IFM takes a participatory, cross-sector and transparent approach to decision-making. The defining characteristic of IFM is integration, expressed simultaneously in different forms: an appropriate mix of strategies, carefully selected points of interventions, and appropriate types of interventions (structural or non-structural, short- or long-term). An Integrated Flood Management plan should address six key elements that follow logically for managing floods, extensively described in the Concept Paper on Integrated FloodManagement (WMO, 2009):

- Manage the water cycle as a whole;
- Integrate land and water management;
- Manage risk and uncertainty;
- Adopt a best mix of strategies;
- Ensure a participatory approach;
- Adopt integrated hazard management approaches.

2.3 Notions and components of risk

18 Both umbrella documents call for a thorough identification and assessment of flood hazards and risks for developing policies, procedures and practices to avoid, control, reduce, or eliminate unacceptable risks and respective disaster losses (flood risk management). In Europe, for instance, the European Directive 2007/60/EC on the assessment and management of flood risks explicitly demands European Member States to prepare preliminary flood risk assessments and flood hazard and flood risk maps where real risks of flood damage exist (EXCIMAP, 2007b). Such tools are indispensable for integrated flood management and are integrated, e.g. in the UK through the Strategic Flood Risk Assessment (SFRA) in all planning processes[3].

3 The UK Environment Agency provides the Flood Risk Standing Advice, which is a tool to help local planning authorities establish the level of environmental risk involved with planning applications. www.environment-agency.gov.uk/research/planning/82584.aspx.

19 To follow an integrated approach to flood management, it is beneficial to understand the notion of risk (definitions are those of UNISDR, 2009) and the components of risk as well as its mathematical definition:

– Hazard: A dangerous phenomenon, substance, human activity or conditionthat may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage;
– Vulnerability: The characteristics and circumstances of a community, system or asset that make it susceptible tothe damagingeffects of a hazard. There are many aspects of vulnerability, arising from various physical, social, economic, and environmental factors. In common use the term "vulnerability" includes both, exposure and susceptibility. In addition, vulnerability is often mixed with aspects of risk or with risk itself. For flood mapping purposes it is necessary to distinguish between the three;
– Exposure: People, property, systems, or other elements present in hazard zones that are therebysubject to potential losses. Measures of exposure can include the number of people or types of assets in an area;
– Risk: The combination of the probability of an event and its negative consequences.

Mathematically risk can be expressed as follows:

*Risk (probable loss) = probability * consequence = p [H] * v[D] * s[H, D]*

where

p [H] = probability of occurrence of the hazard;

v [D] = value of the elements at risk, which is a function of the development in the exposed areas, the land use and the probability of presence (exposure); and

s [H, D] = the susceptibility of the elements at risk, which is a function of the magnitude of the hazard as well as the socio-economic construct of the exposed elements (vulnerability).

20 The probable flood loss is given in economic terms or in human losses. The risk as interplay of the three components, and the respective risk reduction can be shown using a simple graph:

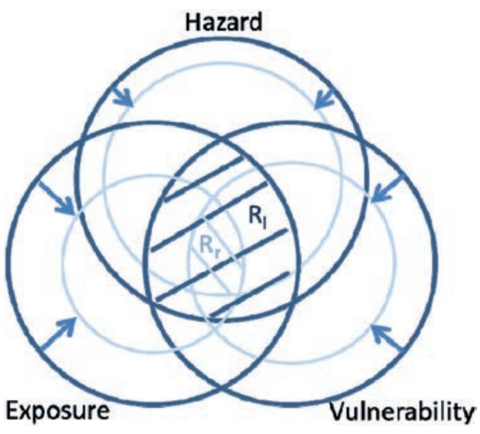


Figure 4 — Risk as a combination of hazard, vulnerability and exposure

21 **Figure 4** indicates the composition of risk (Ri = initial risk) as a combination of hazard, vulnerability and exposure. The arrows indicate risk reduction (Rr = reduced risk), which can be effective for all components to a various degree.

2.4 Institutional and legal requirements

22 The start of a flood mapping exercise requires institutional, administrative and programmatic decisions before the technical parts of the programme can be implemented: first and foremost active stakeholder participation is necessary before legal and administrative mechanisms can be developed **(Figure 5)**. The mapping programme then requires a number of policy decisions.

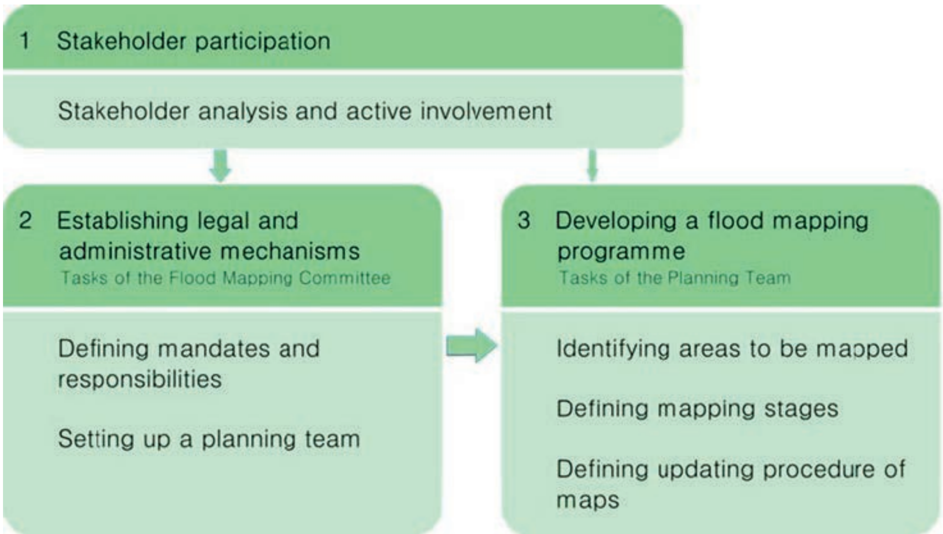


Figure 5 — Steps of institutional and legal requirements for flood mapping

2.4.1 Step 1: Stakeholder participation

23 The "client" for flood maps is more than simply a "user". Users are important stakeholders in the whole Flood Mapping Process (**FMP**) as this process is not only a technical exercise but one which requires extensive, multi-stakeholder engagement through consultative processes. Understanding the various stakeholders' needs and mandates is a prerequisite underpinning the FMP. Political, legal, administrative and/or financial considerations affect who participates in the development of flood maps. As such, it is important to undertake a stakeholder analysis as the very first action in any flood mapping process.

24 In designing the participatory process, the sphere of influence of each stakeholder must be identified and an appropriate participatory mechanism must be adopted. It is crucial to have local involvement and participation (ownership). Relevant stakeholders are:

- Decision-makers: All those who have the powers to make decisions according to defined mandates and responsibilities must be included in governing the FMP;
- Map users that are directly involved in flood management (e.g. emergency managers, land-use planners);
- Flood-prone communities: on a local level, the participation of the flood-prone population is essential;

– Specialised services and specialists who own and provide data, who analyse and evaluate data (like hydrologists, hydraulic experts, modelling experts or similar technical personnel) and other related parties;
– Other programme constituents that may play lesser, but nonetheless important roles in the process like professionals from surveying and mapping, public works, storm-water management agencies, home builders, etc.

25 While the minimum regulatory requirements of stakeholders' involvement must be met, additional outreach is likely to be beneficial to all parties involved to maximize usefulness of the new or updated flood hazard data, to encourage state and local ownership of the maps, and to explain and provide incentives for good practices.

2.4.2 Step 2a: Legal mechanisms

26 The preparation of flood maps has to be guided through a legal framework which clearly defines the authority of producing and disseminating flood maps, defines roles, responsibilities and obligations of all involved departments, institutions and other stakeholders, and lays down clearly defined and transparent processes.

27 Of particular importance are data and information. Assessment and mapping requires a vast amount of data and information to be collected and shared by various institutions under different administrative jurisdiction. Obtaining access to this range of data, synthesizing (using a scientifically valid methodology), and interpreting it appropriately for decision-making or policy setting is inherently a multi-disciplinary undertaking.

28 In many countries the responsibility of developing and implementing flood management programmes are assigned within the law, clearly defining the responsibilities of the federal, state and local authorities; however, more often than not legal provisions, clearly defining the responsibility of providing flood risk information and the related mandates are missing.

2.4.3 Step 2b: Administrative mechanisms and institutional arrangements

29 In the absence of a legal framework, it is important to create a mechanism for enabling close partnership among the institutions involved in the flood mapping programme. Establishing a high level mechanism, such as a flood mapping committee, that represents all the major institutions that have to play an active part in the process of designing, implementing and using the programme and to address the interests of all other stakeholders is essential.

30 The Flood Mapping Committee (FMC) is a high level mechanism aimed to establish, maintain and improve close partnership among the institutions involved in the flood mapping programme. The formation of such committee is highly recommended for a major mapping programme. The membership should be guided by the present mandates of the lead institution(s) responsible for implementation of the FMP. The committee should have at least one representative from the following institutions:

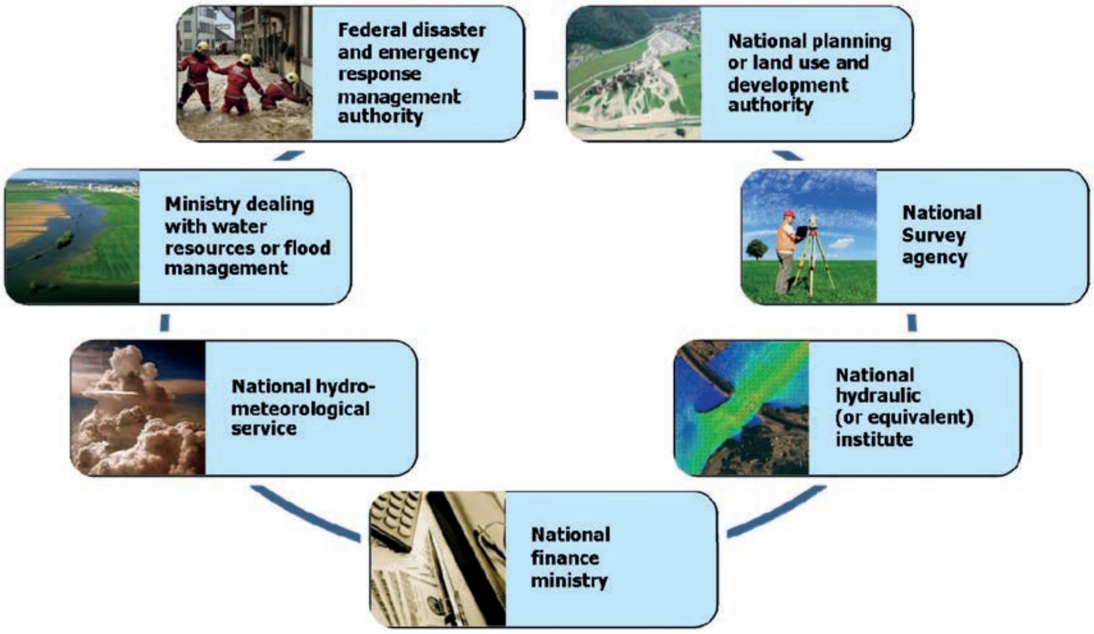


Figure 6 — Represented fields and disciplines in a Flood Mapping Committee

31 A range of other relevant institutions can be invited depending on the given administrative arrangements within the country. Such a committee can be enabled through an executive order and should be adequately empowered. The committee should have the mission to "ensure the availability of consistent and accurate flood hazard information to all the stakeholders involved in integrated flood management". In particular, the FMC should:

- Facilitate establishment of a flood mapping programme within the country or region;
- Provide policy guidance;
- Arrange resources for its implementation;
- Monitor progress related to programme implementation;
- Set standards and protocols for production and dissemination of flood information;
- Encourage strong federal, state, regional and local partnerships in the programme.

32 Given the geographical and administrative situation, similar authorities at the sub-national or river basin level may be required. The engagement of local authorities who are mainly responsible for the implementation of flood management projects and who respond to the emergency situations is of particular importance.

33 The design of a mapping programme requires, as a second entity, a planning team (PT) consisting of key technical experts. The planning team plays a vital role in drawing up the FMP and is responsible for its implementation. The PT members can be categorised as:

i data providers facilitating full access to relevant terrain, hydrological and other data;

ii specialists assessing hazards, exposed assets and their vulnerabilities (for example, hydrologists, hydraulic engineers, geographers); and

iii users of flood maps, i.e. flood risk managers, land-use planners, disaster response authorities, flood insurance companies etc.

2.4.4 Step 3: Developing a flood mapping programme

34 The Planning Team **(PT)** will start its activities with a scoping exercise which enables the development of a comprehensive concept paper. Such document clearly outlines:

- The rationale for flood mapping (why we are implementing flood mapping?);
- The specific flood management decisions it is intended to support;
- The intended audience (who is using the maps?), including the necessary dissemination process and mechanisms;
- The status of flood mapping in the country and gap identification;
- The data requirements and availability (who can provide what type of data and what state of updating?);
- The availability of technical expertise (who has the knowledge?), and
- The future action plan, including the long-term update process, along with the financial resources required.

35 The identification of flood hazards is often carried out in conjunction with identification of other hazards in order to produce multi-hazard maps and management programmes. The concept paper should consider such a possibility. With the approval of the FMC, the concept paper can then serve as the guiding document for further steps until a flood mapping programme is fully developed. Based on the concept paper, the committee could also advise various stakeholder institutions involved to bridge the gaps in capacity, if any, in their contribution towards a successful flood programme. The Committee should provide the necessary proposal for financing the programme, including resource mobilization to the government and facilitation.

36 The concept paper developed by the PT will be refined, during subsequent stages, into a flood mapping programme **(FMP)**. The FMP is a combination of activities or projects that meet the objectives set out in the concept paper; it should clearly identify the areas to be mapped and define the needed mapping stages and updating procedures of maps (also see **Section 3.2**).

3 FLOOD MAPPING: PROCESS AND PRODUCTS

37 Flood mapping is a technical and administrative process. Whereas the term flood mapping explicitly describes the development of flood maps, the term implicitly incorporates flood assessment; that is the analysis of various data and parameters representing flood conditions (past floods, flood prediction) in a flood plain, covering a whole river basin, along an individual river reach or on an alluvial fan. The areas on alluvial fans potentially affected by mud flows or debris flows are similarly addressed using additional information about sediments and sediment transfer (WMO, 2011b).

38 The results of a flood assessment in a particular area are commonly represented on maps, such as a flood hazard map, flood risk map or any other map used in the flood management process. Depending on the purpose, distinct stages of flood assessment are known: preliminary and detailed flood assessments are most common; in some instances a general purpose assessment is used as an intermediary stage (this guidance does not make special reference to this stage). In each of these stages one or several approaches (historic, geomorphic or modelling approach) are applied. The following sections will highlight the various aspects of flood assessment: in the last two sections the flood mapping process itself is outlined and its products are presented.

3.1 Flood assessment stages (policy)

39 Flood assessments can be implemented in different stages. The stages differ mainly with regard to the technical depth of the assessment and with the approaches used. The stage decision occurs in an early phase of the mapping programme (see also **Section 3.3**) and is mainly a policy decision. The three stages are summarized as follows:

3.1.1 Preliminary flood assessment

- **Information provided:** First perspective on the flood problem through flood inundation maps, generally carried out for a country or province, part of them, or for a river basin. Combined with macro-scale vulnerability, they provide the basis for preliminary flood risk maps and the delineation of "hot spots" of damage;
- **Degree of details and scale:** Accuracy, assessment depth and scale are limited (map scales may vary between 1:100,000 and 1:500,000; smaller scales are of little technical value;
- **Description and necessary steps:** Starts with the identification of flood hazards of all types from all sources using mainly the historical and geomorphological approaches. It forms the first step towards a subsequent general or detailed assessment. Preliminary assessment does not require extensive data and thus provides an opportunity to prepare for more detailed assessments;
- **Links and sources:** EU flood directive requests such assessments every 6 years in the form of the EC Water Reporting Obligation (EEA, 2009); Information on how to establish such preliminary flood risk assessments is available, e.g. at the UK's Environment Agency (EA, 2010).

3.1.2 General purpose flood assessment

- **Information provided:** Provides analysis of flood hazards in a predictive mode and the likely social and economic consequences. The driver for this assessment may come from the disaster management, flood management or land use management perspective, mostly after a major flood event;
- **Degree of details and scale:** May cover a vast area; therefore, the scale may range between 1:50,000 and 1:250,000;
- **Description and necessary steps:** It is a process that requires extensive planning, data gathering and management, technical expertise and above all clear definition of roles and responsibilities.

3.1.3 Detailed flood assessment

- **Information provided:** Provides tailored information about flood prediction for a specific location on a flood plain, along a particular river reach or on an alluvial fan. This information can be used to support various types of policies and plans for flood management, to make well-identified decisions by choosing from various possible flood reduction options and implementing the chosen measures;
- **Degree of details and scale:** Mapping the results of detailed flood assessments occurs on a detailed scale, normally better than 1:25,000, in some instances even better than 1:5,000;
- **Description and necessary steps:** It is a process that requires extensive planning, data gathering and management, technical expertise and above all clear definition of roles and responsibilities;
- **Links and sources:** Assessment of flood risks in the flood-damage-reduction approach by the United States Army Corps of Engineers (USACE, 1996). The Risk Mapping, Assessment, and Planning RiskMAP programme by FEMA builds on flood hazard data and maps produced during the Flood Map Modernization (Map Mod) programme (FEMA, 2009b).

3.2 Flood mapping process: Concept and implementation (technical)

40 The technical development of flood maps is an iterative process, and fully depends on local conditions guided by the following issues:

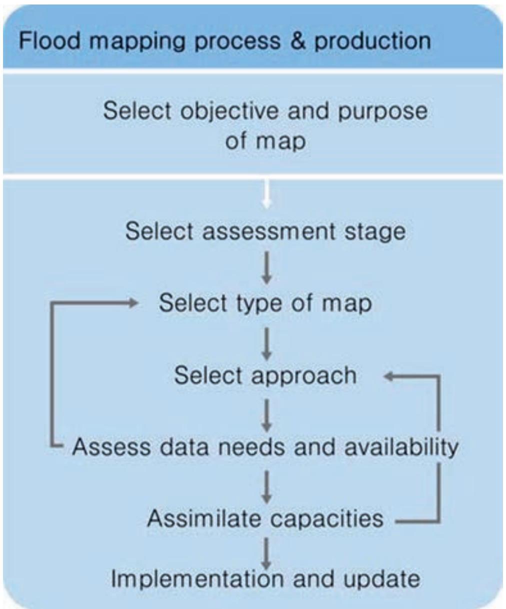


Figure 7 — Steps of the flood mapping process and production

The implementation of flood assessments and development of flood maps require some relevant considerations prior to the programme launch:

3.2.1 Objectives

41 The concept paper established by the planning team describes the objectives of the flood mapping programme. In particular the following questions need to be answered:

- Purpose: What are these maps produced for?
- Target audience: Who is using the maps?
- Target area: Which areas are covered? (river basin, particular flood plain, river reach, particular settlement, a whole province etc.)

3.2.2 Type of maps

42 The choice of mapped parameters and type will depend upon the objectives of the project, the resources available and the potential benefit achievable. The following maps are relevant. Definition of maps are given in **Section 3.3**:

- Event map;
- Hazard map;
- Vulnerability map;

– Risk map.

43 The approach to mapping may be different depending on the stage of mapping (preliminary, general purpose or detailed; see **Section 3.1**), the use and the availability of data. Therefore, selection of the type of flood map and its specifications would have to be revisited.

44 The key parameters to be included in the maps should be selected and discussed with the users and submitted to the FMC for peer review as appropriate. If external contractors are deployed for the preparation of maps, these specifications becomes very crucial as costs for producing maps with different scales or specification may entail an increase in the magnitude of costs by several orders.

3.2.3 Mapping approach and methodology

45 Flood hazard maps alone serve many purposes. They can be directly implemented (e.g. in land-use planning processes), but are also the main input for vulnerability and risk maps and serve for the production of various end-user instruments. Therefore, flood hazard maps are fundamental to the entire mapping process, particularly in the beginning. Three different approaches to develop flood hazard maps (further described in **Sections 4.2** and **4.3**) are:

– Historic approach is based on past flood events: Written reports, old maps or photographs or any other document may provide relevant information to delineate flood zones. Currently, satellite imagery supports mapping of near real-time flooding. The historic approach supports preliminary and general purpose flood assessments and their respective maps. It is often used for the validation of the detailed mapping stage;

– Geomorphologic approach: Floods and flows leave distinct marks of past events in the landscape. These marks can be read and interpreted. Flood extent and, to a certain degree, other parameters for the magnitude can also be derived. The geomorphologic approach serves the preliminary and general purpose flood assessment and their respective maps. It is often used for the validation of the detailed mapping stage;

– Modelling approach: Hydrological and hydraulic models are applied to simulate floods of a particular magnitude occurring in a channel/channel system. In general, the modelling approach serves the detailed flood assessment. It addresses the estimation of design floods (flood hydrography) as well as the flooding process (hydraulic modelling).

46 The choice of approach is largely governed by the mapping stage, the purpose, the availability of data and to a certain extent the availability of expertise in the country. The historic and geomorphologic approaches are mostly used in the preliminary stage, whereas the modelling approach is mainly used in the detailed mapping stage. Given a particular approach, the availability of data will influence the scale of the map that could be developed and the particular methodology that could possibly be adopted.

3.2.4 Data needs and availability

47 Flood assessment including mapping inherently involves various data sets (also see **Section 4.1**):

– Topographic data: Topographic maps with contours, satellite imagery, air photographs, digital elevations models, river cross-sections and similar data. Currently, remote sensing provides data and information which is particularly interesting to explore in data-sparse conditions (e.g. in developing countries).

– **Magnitude of hazard:** The magnitude of the flood hazard is a function of the physical environment. Data sets include rainfall, snow cover, stream gauge, and hydraulic data (channel geometry, bed roughness etc.).
– **Exposure:** Exposure is a function of socio-economic activities. Data are: built structures, population, economic value of exposed assets etc. Such data are not always readily available.
– **Vulnerability:** The characteristics of the exposed assets or processes which make them more or less likely to experience damage or loss. Often such data are not available. As a minimum, vulnerability classes have to be attributed to land-use classes, such as housing estate, industrial complex, transport infrastructure, etc.

48 It is desirable that the data in all the above categories are readily available for flood mapping. A comprehensive assessment is required of all available data, their forms and formats of storage, and their data sharing policies. As far as possible these data sets should be collated into a single database so that they are available to those who develop the flood mapping programme and who are responsible for developing specifications for the map products. The comprehensive data assessment should clearly identify gaps. Where the required data are not available, the relevant agencies should be sensitized, through the Flood Mapping Committee, to develop a programme to collect such data where they exist or to start generating such data where they do not exist.

49 Establishing key partnerships with states, counties, cities, academia, and the private sector could help increase data availability. Efforts should be made to develop a mechanism for national flood hazard data generation, maintenance and sharing similar to the mechanisms for national planning data. Such a mechanism would:
– Reduce duplication of effort among agencies;
– Improve quality and reduce costs related to flood information; and
– Increase the benefits of using all available data.

3.2.5 Required capacity

50 Successful implementation of a flood mapping programme, in addition to the legal and institutional arrangements described earlier, requires human resources, expertise, equipment and supplies. The costs of these inputs make up the project budget, yet further requirements can be met once the financial resources are tied up. Knowledge and technical expertise, particularly in various fields such as geology, surveying, hydrology, and hydraulic analysis, may be difficult to arrange for a self-sustained long-term flood mapping programme. Therefore, it is important to assess the expertise available within the partner agencies, university and research institutions and the private sector, and to identify the gaps in skills.

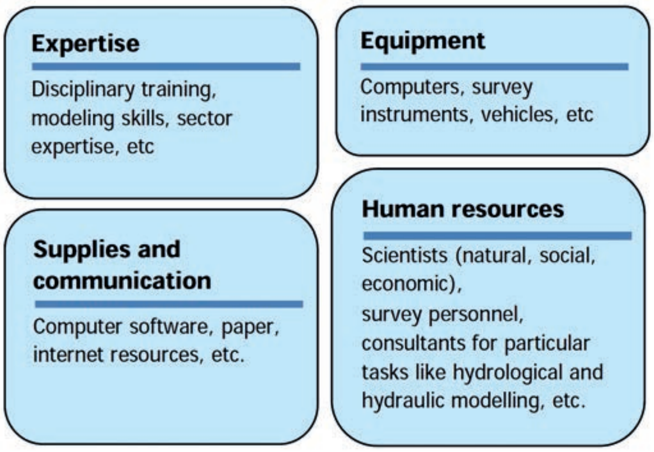


Figure 8 — Capacity requirements for flood assessment and map development

51 A comprehensive capacity building exercise should be planned that would include technical training in all topics where the required expertise is unavailable, such as analysis of hydrological data, data management using Geographical Information Systems (GIS), hydraulic modelling, geomorphologic field analysis etc. The Flood Mapping Committee should address the need for closing the gap in the long-term through intensive on-job trainings in specialised skills, and if required, through specialised courses at universities.

3.2.6 Implementation and update process

52 The flood mapping exercise may be implemented in a concerted action. If resources are limited or procedures are not fully clear, a step-wise process can be envisaged, preferably implementing a pilot project in a limited area with subsequent up-scaling when more resources are available and procedures are clarified. In any case, a timetable for map generation needs to be established.

The updating process has to be defined before the mapping starts. Basic maps need to be updated according to the need:

- **Event map:** Whenever a flood occurs the information should be integrated in the available data base and shown on the map;
- **Hazard map:** Updating should occur regularly (e.g. every 10 to 15 years) or after new information is available; this might be a major event or new knowledge, know-how and technologies to assess the respective hazards;
- **Vulnerability and risk map:** The built environment is rapidly changing. New developments might considerably change the vulnerability; it might even change the hazards. Therefore, the map updating should occur at the same pace as for the hazard map or any major change in the flood plain or on the alluvial fan;
- **End-user map:** Regularly (same pace as for the hazard map); and according to the need expressed by the user.

3.3 Products of flood mapping

53 Flood maps exist in a large variety, having various content, various scales, and fulfilling different objectives. The basic flood maps and few applied maps are briefly described in the following sections providing an example for each type:

- **Preliminary flood map:** Most of the types of flood maps described further down may be developed first as preliminary flood maps;
- **Event map:** Showing one or several past events;
- **Hazard map:** Various parameters describe the hazardous process;
- **Vulnerability map:** Susceptibility of structures to magnitude of hazard;
- **Risk map:** Risk as probable loss, also hot spots which require remedial measures;
- **End-user map** (flood zoning, emergency, insurance, etc.)**:** There is a variety of end-user maps. They are all deduced in one or the other way from the base maps. The end-user maps address different planning issues and are developed according to the need. Here only end-user maps (flood zoning and emergency map) are briefly described. An example of an preliminary flood insurance rate map can be taken from (Falmouth GIS 2013).

Detailed descriptions and examples for each flood mapping product are given on the next pages.

	Preliminary flood map
Definition	Small scale overview maps indicating general or particular flood hazards or flood risk problems in a basin or a part of a country. They are the first step towards a more detailed mapping.
Content	The main objective of preliminary flood mapping is to define the decisive flood processes (flooding, mud flows, flash floods etc.) and the outer limits for an extreme event. By superimposing the potentially affected areas with land-use maps (or other parameters representing damage potential) the "hot spots" can be determined (European Flood Directive, 2007). As such, such maps represent simplified risk maps. The preliminary map can form a basis for general purpose or detailed assessment. If this is not intended and the preliminary map serves as the final product, it should include as little information as possible but as much as necessary based on further sources, such as historic sources and assumptions on severe scenarios.
Scale	The flood-affected areas are provided as an overlay to the existing topographic, satellite or land-use maps. The scale of such maps may vary from 1:500,000 to 1:25,000 depending on the size of the basin or area to be represented.
Purpose and use	The preliminary flood map serves strategic planning. The objectives include: – Flood mapping programme: an inventory of the typology of flood processes and areas affected by these floods needs to be prepared. – Public awareness: maps can be a trigger to inform general public on existing hazards and risks and can help explain priorities. – Regional or national planning: On the strategic level an overview is needed on the various natural and man-made risks for resources allocation. In areas with limited human activities the knowledge of the type of hazard is relevant for decision making on future development of the area. – Emergency planning and risk management: maps are an important tool to set priorities since highest risks should be mitigated first. – Flood management: maps are a must for basin-wide flood management planning, particularly for transboundary basins.

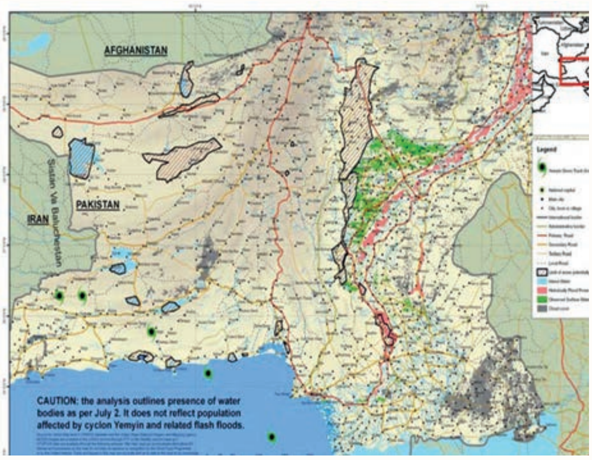


Figure 9 — Preliminary flood analysis map cloud-free areas based on MODIS imagery, Pakistan 2007
Flood analysis outlines presence of water bodies (green), and historically flood prone areas.
It does not reflect population affected by the cyclone and related flash floods.
Detailed maps at: www.unitar.org/unosat/node/44/930 (UNOSAT)

	Flood event map
Definition	Flood event maps show the observed flood events and their extent as recorded by different means.
Content	Flood event maps are based on floods which occurred in the near or far past. The information for the event can be collected from a variety of sources. Apart from historical documents, use can be made of satellite images. All of the sources of information require interpretation and verification before use. The information may include floodplain boundaries, recorded flood level, depth and flow as well as extent and incidence/ occurrence, regulatory floodway boundaries, base flood elevations, or flood cross-sections.
Scale	The scale of flood event map may vary considerably between 1:5,000 and 1:250,000, depending on the basin size that is being mapped and the information available about the past event (**Figure 10** presents a collection of multiple sites).
Purpose and use	The use of flood event maps is manifold: – Validation of models for flood hazard mapping: past events form an essential step towards validation of the hydrological and hydraulic models. – Awareness raising: past events can be used to raise awareness of the local population. In combination with a hazard map (predicted flood areas) the event map is used to underline the prevailing flood hazard. – Emergency response: The satellite or aerial photography based flood event maps are used for flood emergency response.
Specific Issues	Flood mitigation schemes may have been implemented after the flood event which will have significantly reduced the likelihood of future flooding in the earlier flooded areas.

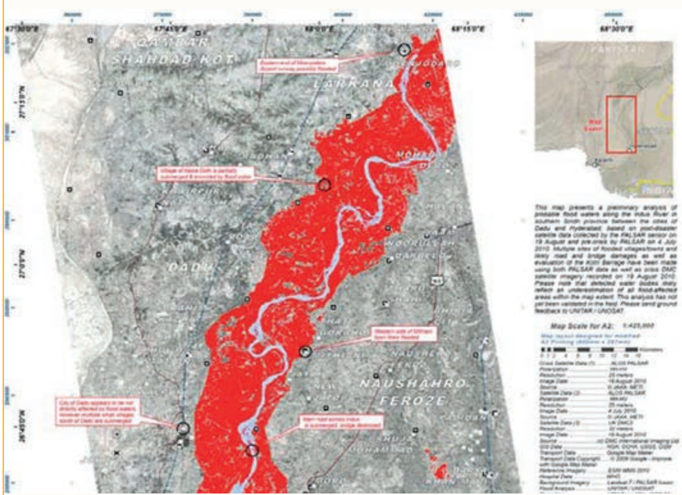


Figure 10 — Flood event map (near real-time) for the Pakistan flood 2010 in the preliminary assessment stage.
Detailed maps at: www.unitar.org/unosat/node/44/1485

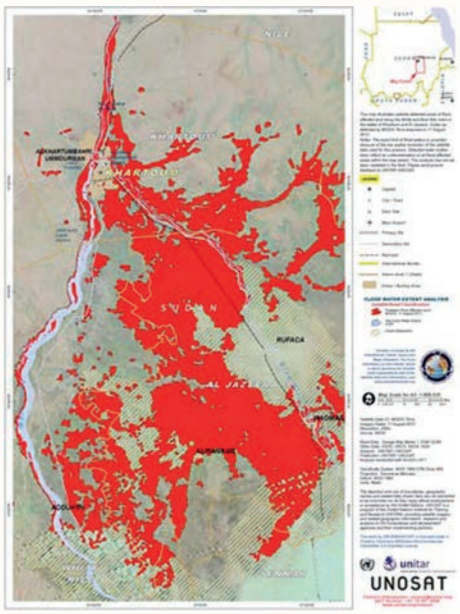


Figure 11 — Flood extent map near Khartoum, satellite-based classification, Sudan.
Detailed maps at: www.unitar.org/unosat/node/44/1796

Flood hazard map	
Definition	A flood hazard map graphically provides information on flood inundation (inundation depths, extent, flow velocity etc.) expected for an event of given probability or several probabilities.
Content	The key items to be incorporated in a flood hazard map for a given probability of occurrence are: – Flood extent (areas covered by water) – Flow velocity (m/s) – Water depth (m) Other hazard parameters represented on a map are, for instance: – Flood propagation (km/h) – Flood depth * velocity (m*m/s; as indicator for degree of hazard)
Scale	The hazard map should be superposed on the available topographic map with ground elevations and physical features. The standard scale of hazard maps is 1:5,000 to 1:25,000. A scale of 1:10,000 is a good planning scale in order to enable identification of individual structures which are inundated. Topographic maps of 1:100,000 or smaller are not suitable. Maps mainly cover populated, developed or developing areas as well as traffic routes.
Purpose and use	The flood hazard maps provide basic information for developing technical guidance on various floodplain management issues and help different stakeholders including local governments make decisions in flood management. Flood hazard maps are important for assessment of flood risk, development of flood mitigation plans, preparing comprehensive flood risk management schemes, and in particular: for local urban planning. Flood hazard maps form the basis for the flood risk maps, flood emergency maps and other related maps.

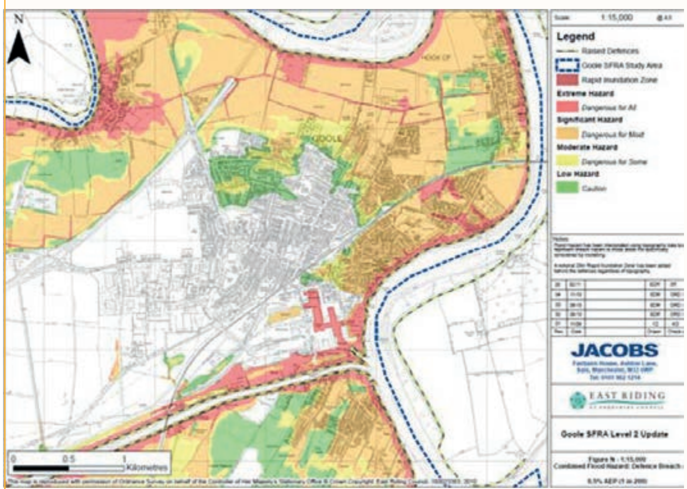


Figure 12 — Combined breach hazard map with identified relevant hazard classification (East Riding, UK)

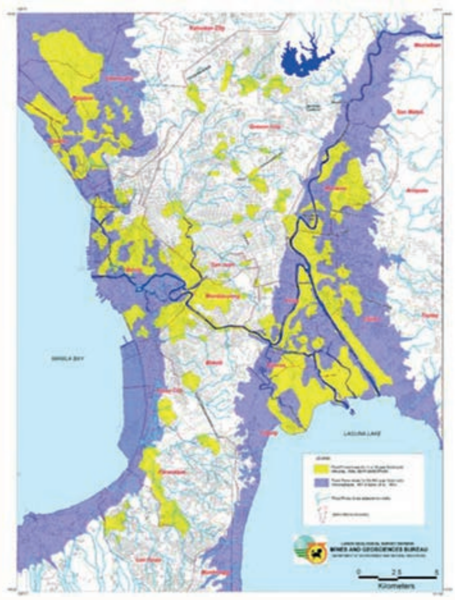


Figure 13 — Flood hazard map of Metro Manila, Philippines (Malaysia Department of Environment and Natural Resources)

Detailed maps at: www.eastriding.gov.uk/corp.docs/forwardplanning/docs/SFRA/Level2/sfraL2FigureN.pdf (East Riding); www.preventionweb.net/files/24897_metromanilafloodh azardmap40kvls1.jpg (Manila)

Flood vulnerability map	
Definition	A flood vulnerability map indicates the potential harm to people, assets, infrastructure and economic activities exposed to flooding either directly or indirectly. It can be presented in quantitative terms or qualitative terms through indicators.
Content	Vulnerability to flooding is dependent on the exposed people, assets, and infrastructure on the one hand and the magnitude of the hazard on the other (most relevant are water depth, flow velocity and duration of inundation). The vulnerability maps may either contain all the above groups of information or build each one as a separate layer. Depending on the scale, content can be generalized using indicators or detailed with priority to exposure of particular groups of persons (e.g. aged, handicapped etc.).
Scale	Scales between 1:100,000 to 1:25,000 are appropriate to obtain an overview of the potential damage. Larger scales (1:5,000 to 1:25,000) are needed for emergency planning, showing e.g. vulnerable populations, including the aged and the handicapped as well as life-line infrastructure.
Purpose and use	– Vulnerability maps provide the basis for flood risk maps that support flood risk management decisions and are the necessary input for emergency planning. – Vulnerability maps are a basis for planning of countermeasures but do not directly lead to action. They show the possible consequences of a flood event on human activity. – For developing insurance maps, the vulnerability of an area in monetary terms is needed to assess their risks.
Specific Issues	Vulnerability parameters may vary rapidly with time. Therefore, a data base should be built to enable regular updating. This is of particular importance for vulnerability maps serving as base for emergency planning.

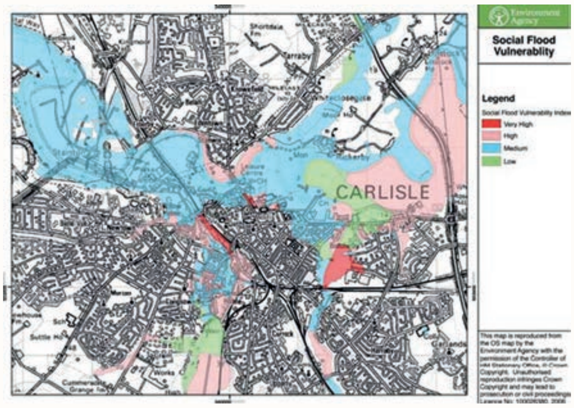


Figure 14 — Social flood vulnerability map, Carlisle, UK (EXCIMAP, 2007b)
Detailed maps at: ec.europa.eu/environment/water/flood_risk/flood_atlas/countries/pdf/uk.pdf

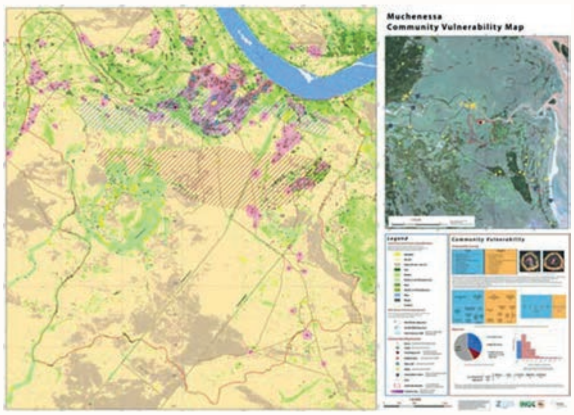


Figure 15 — Community vulnerability map, Muchenessa, Mozambique
Vulnerability assessment based on vulnerability scoring, calculated both from impacts by floods and droughts. Find detailed maps in (Kienberger 2008)

Further examples on the development and use of flood vulnerability maps are given in (Lindley et al. 2011) and (Kienberger 2008)

Flood risk map	
Definition	Flood risk maps integrate the potential hazards with the vulnerabilities of existing or potential economic activities when exposed to floods of a range of probabilities. The term "flood risk map" is frequently used but often not in its narrow sense.
Content	Risk maps are an integration of hazard maps and vulnerability maps, showing the average damage per unit area, often expressed in monetary terms (potential loss per unit area and time). Risk is the only parameter which allows a comparison of different risks and is a necessity in economic evaluation. Although loss of life is sometimes expressed in monetary terms, risk to persons should be shown separately, because the acceptance differs considerably for the different users of the map.
Scale	Since risk is a lumped parameter, the details are less important and scale may range from 1:100,000 to 1:10,000. Differences can be made according to its purpose: the land use (urban settlements, industrial, agricultural) or to the type of damage (monetary, environmental and social).
Purpose and use	Risk maps in the strict sense are an instrument for evaluation. Comparing the risks with and without measures is used to demonstrate effectiveness and economic justification, thus, support priority setting for risk reduction measures. – Flood management: By comparing different risk maps (based on scenarios with and without counter measures) the overall effect of measures can be evaluated, e.g. as part of cost benefit analysis. – Land-use planning: is concerned with future development and therefore needs hazard maps. In risk maps, the consequences of errors in the past can be seen. – Insurance: Risk maps provide information on the value of exposed assets and help the insurance companies to fix premiums for the individual contracts.
Specific Issues	Preliminary flood risk maps can be developed by applying average damage values per unit area (per land use type) on the preliminary hazard maps. However, in the detailed mapping stage, flood risk maps need high accuracy.

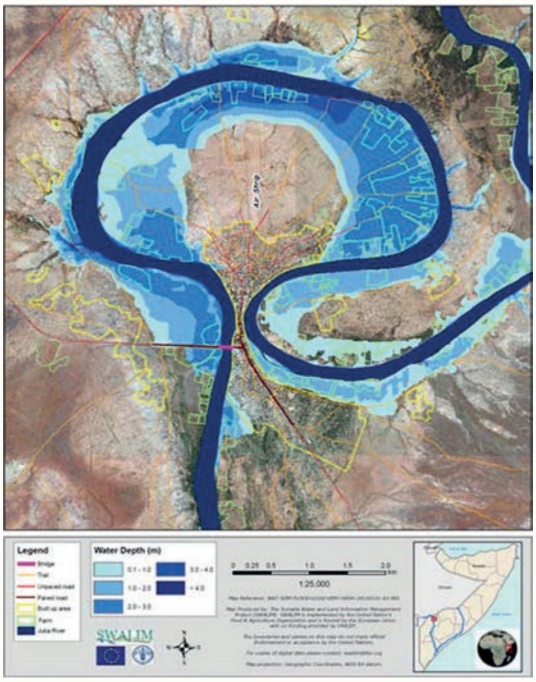
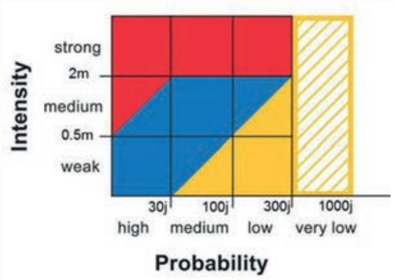


Figure 16 — Flood risk maps for Luuq, Somalia, for 50-year (left) and 100-year (right) return period.
Detailed maps at: www.faoswalim.org/subsites/frrims/

Flood zoning map

Content	Flood zoning maps can be considered as 'adapted' flood hazard maps for planning purposes. The zones show existing hazards, often classifying them as low, medium or high hazards. This map is based on a hazard map and makes provision for the land-use in a particular area.
Purpose and use	Planners are concerned with locating areas with limited exposure to hazards for various uses: human settlements, industries, infrastructure, and agriculture. Land use planning does not influence the existing risks, yet changes in land use can be induced. This is normally very difficult since existing rights must be compensated. However, it is the most effective measure to slow down the present continuous increase of risk and damage potential. Building codes must be linked to the hazard zones. Prerequisite is that construction is adapted to the hazard situation.

A system used in Switzerland and parts of Germany and Italy for the development of detailed hazard zoning maps is based on a combination of probability (recurrence interval of 30, 100, 300 years) and magnitude (three levels) to express four hazard classes (BWW et al., 1997).



The example above shows four degrees of danger. Building restrictions are used for the three main colors:

- Red: elevated danger – prohibited area
- Blue: medium danger – building with restrictions, conditional use area
- Yellow: low/residual danger – awareness zone, elevated danger, building allowed with restrictions for sensitive elements
- Yellow-white: indication of an extreme event that is not considered for land-use decisions.

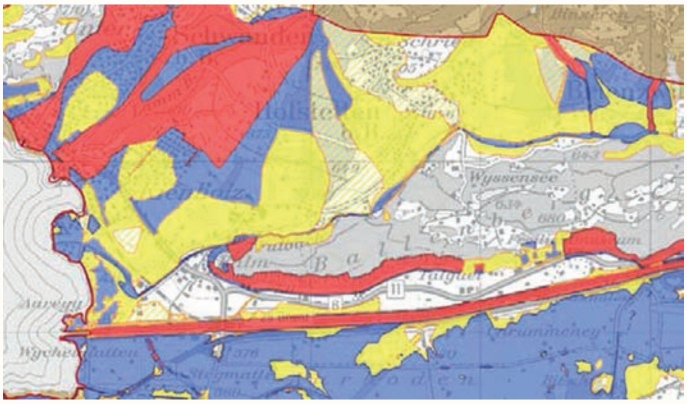


Figure 17 — Hazard zoning in the valley bottom (flooding) and on alluvial fans (debris flows)
Official hazard zoning map, Brienz, Canton Bern, Switzerland

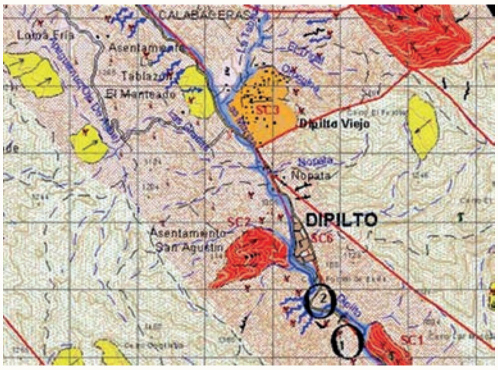


Figure 18 — Hazard zoning indication map on landslides and flooding with Swiss system applied in Nicaragua (República de Nicaragua, Municipio de Dipilto.
SDC's disaster reduction programme for Central America, Managua, 2003 in SDC, 2005

Flood emergency map	
Content	This map is based on hazard, vulnerability and risk maps, depending on purpose. Flood emergency response needs careful preparation since time to respond is a limiting factor. Emergency preparedness plans are based on various likely scenarios that could develop during flooding, including the worst scenarios.
Purpose and use	Warning, emergency planning and rescue operations are closely linked. Forecasting and warning are essential elements in risk management to avoid loss of life. Flood maps can define the region or the locations for which the forecast must be established and evacuation routes and safe havens may be indicated. Flood emergency maps are developed on a needs basis. However, the proper base map and additional information is relevant for a smooth implementation in case of emergency. The example shows particular cases.

Figure 19 — Flood emergency map of 2007 in Budalangi, Busua Districtt, Kenya (The Daily Nation, Standard, & DEPHA; UNOCHA) Find detailed maps here: http://reliefweb.int/map/kenya/kenya-floods-budalangi.busia-district

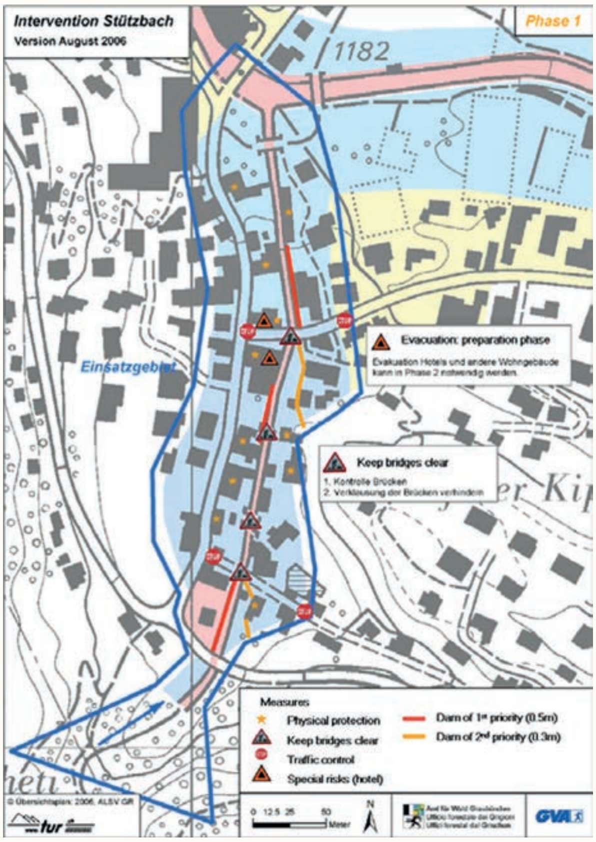


Figure 20 — Emergency preparedness and management map; example from Davos municipality, Switzerland (modified after Romang, 2006)

4 MAP PRODUCTION: TECHNICAL CONSIDERATIONS

4.1 Data: types and sources

54 Flood mapping heavily depends on data. Depending on the methods and techniques chosen, the need for accurate data is high. However, in many places basic data (terrain, hydrological or economic) are hardly available; if available they are sometimes outdated, are available only in analogous form or are rather expensive. In a number of cases, the data (e.g. adequate topographic maps) may be available; however its access is restricted.

55 This section briefly outlines the specific data needed for flood assessment and mapping, describes available data sources, and provides information about models to be used for flood mapping. Additional information about data management (collection, processing and storage), and hydrological and hydraulic processing is available in several **Annexes**.

4.1.1 Topography

56 Topographic elements of the natural and built-up environment play a vital role in any type of flood assessment and mapping. The main sources of information are:

- Topographic maps;
- Aerial photography, orthophoto maps;
- Satellite imagery.

57 The national geodetic survey, land cadastre or similar services may provide the relevant products. Satellite imagery is a viable alternative if up-to-date topographic maps are not available. Nowadays, Google Earth provides excellent imagery for almost all corners of the world in good to very good resolution.

58 Additional data on the global level can be found in **Annex 1**. In addition, many topographical data are supplied on data CDs/DVDs by ESRI accompanying the ArcGIS software package.

4.1.2 Surface elevation

59 The importance of terrain data surpasses any other data need. Topographic maps with contour lines are a well-known data source. However, maps might have limited accuracy. Digital terrain models (DTMs) have been developed since the 1990s. Today, DTMs are standard for a number of applications, such as:

– Preliminary mapping: CGIAR data available as 30 m raster formats (see **Annex 1**). The accuracy is limited; however, such data might be used for large flood plains or alluvial fans.

– Detailed mapping: The national geodetic survey may provide DTMs in sufficient resolution, based on e.g. Laser Imaging Detection and Ranging (LIDAR) survey.

60 The terrain (contour lines) given in topographic maps can only be used in limited cases for the development of a Digital Terrain Model (DTM) of the ground surface. The quality of a DTM, derived by photogrammetric methods, gives the elevation with an error of +/- 1.0 m and more. This is often not sufficient. LiDAR[4] provides accurate information but is a rather expensive way to determine a DTM with a spatial resolution of 1 to 2 m and an error in the elevation height of less than +/- 10 cm. The definition of break-lines at all discontinuous changes of the topographic height is important for an accurate numerical model, e.g. at foot and upper edge of the river banks and at the shoulders of a dike.

61 In 1-dimensional hydraulic models cross-sections of the expected inundated part of the flood plains and the river are the topographic basis. For high quality of hydraulic modelling it is recommended to keep the distance of the river profiles below 100 m. Further refinement is needed at hydraulic structures like bridges, weirs and sudden changes of the river bed.

62 For 2-dimensional flow modelling the DTM of the ground surface and bathymetry can be directly used for the development of the numerical grid. Some grid generators are available which try to automate this process. The definition of break-lines at all discontinuous changes of the topographic height is important for an accurate numerical grid.

4.1.3 Past flood events and disasters

63 Information about past (historic) events is an important input for the assessment of hazards, vulnerabilities and risks. The relevant information can be found for nation-wide events (e.g. international and national data bases or on a local level with newspaper archives, local authorities or, for individual spots, with elderly people or flood marks):

4 More information on LiDAR can be found for instance at: lidarnews.com/

Table 2 — Databases for information about past and present events

Source	Institution	Content
International data bases	Centre for Research on the Epidemiology of Disasters (CRED)	EM-DAT: International Disaster Database for individual events Link: http://www.emdat.be/
	UNITAR's Operational Satellite Applications Programme (UNOSAT)	Satellite imagery analysis and satellite applications to provide maps (flood extent maps etc.), reports and GIS data; Humanitarian Rapid Mapping Service Link: http://www.unitar.org/unosat/
	United Nations Office for the Coordination of Humanitarian Affairs (UNOCHA)	Humanitarian information on global crises and disasters –global reports maps and data available on http://reliefweb.int/ UN/EC Global Disaster Alert and Coordination System (GDACS) provides access to web-based disaster information systems, disaster related reports and related coordination tools - Link: http://www.gdacs.org
	Dartmouth Flood Observatory	Space-based Measurement and Modeling of Surface Water for Research, Humanitarian, and Water Management Applications Link: http://floodobservatory.colorado.edu/
	IASC Humanitarian Early Warning Service (HEWS)	Global multi-hazard watch service to support humanitarian preparedness, early warnings and forecasts for natural hazards Link: http://www.hewsweb.org/hp/
	Munich Re NatCatSERVICE	Natural catastrophe loss database: Maps and statistics for particular types of natural hazards – Link: www.munichre.com/geo
	Corporación OSSO, LA RED, UNISDR: DesInventar	Databases of emergency or disaster losses and damages; covers countries in Latin America, Africa and Asia Link: http://www.desinventar.org/en/
	EU Copernicus GIO Emergency Management Service (GIO EMS) – Mapping	Timely and accurate geospatial information derived from satellite remote sensing Link: http://emergency.copernicus.eu/mapping/ems/ems-mapping-service
	World Food Programme Map Centre	Provision of maps that contain information useful to aid professionals, including rainfall, flooding, transport links, earthquake effects and storm damage Link: http://www.wfp.org/aid-professionals/map-centre
	ESA Fully Automatic Aqua Processing Service (FAAPS)	FAAPS to support emergency management professionals with the provision of flood extent maps even in rain conditions and over large areas Link: http://desktop.faaps.eu/
National databases	National statistical services	Disaster data
	Crisis management agencies; environmental agencies	Information about individual events
	National Newspaper archives	Individual events
	National insurance companies	(often not open to public)
Local information	Newspaper archives	Reporting about past events and impacts (caution on accuracy)
	Local disaster management authorities	documentations of past events maps, reports, photos, etc
	Monuments and marks of past events	Individual events
	Elderly persons	Information often 50+ years back Interviews (standardized)

64 The retrieval of historic flood data is rather time-consuming and the interpretation of such data requires care (see **Section 4.2.3** on historic approach.)

4.1.4 Hydrologic data

65 Hydrologic data are relevant to estimate peak discharge, for the construction of hydrographs or for the estimation of discharge-frequency relations. Hydrologic data are commonly available at:

- The Hydro-meteorological Service (rainfall and discharge measurements);
- Water authority, in relation to water use;
- Hydro-electric power stations;
- Global Runoff Data Centre (GRDC), Koblenz, Germany: a repository for the world's river discharge data and associated metadata.

66 Time series of rainfall and discharge data should be as long as possible. Thirty or more years of continuous measurements provide the possibility to analyse the data statistically.

4.1.5 Hydraulic data

67 Hydraulic data describe the discharge conditions in and around the channel. Three spatial sections and the respective roughness are relevant: flood plain – river bank – riverbed (cross-section). This is well described in many standard hydraulic text books, like the well-known Open Channel Hydraulics (Ven Te Chow 1959) or many publicly available scripts (e.g. Goodwill & Sleigh, 2007).

68 Relevant input for the hydraulic models is the roughness distribution and the parameters of the flood plain and in the river bed to determine flow resistance. A reliable evaluation of the roughness parameters needs good experience. Aerial images, land use maps and biotope distribution maps can be used for a first classification of roughness zones but results require thorough field check. The best basis to evaluate the roughness in the river bed would be through taking bed material samples at various locations of the aquatic zone and determining the grain size distribution curve in the laboratory. But often only visual control of the bed material is possible. An intermediate solution is the "transect-by-number" sample of the armour layer (Anastasi 1984; for application see Bunte & Abt, 2001).

69 For the validation/verification of the hydraulic model, recorded water levels and delineation lines of the inundated area should be available for historic floods and at normal flow conditions. The flow conditions below bankfull discharge serve for the validation and the verification of the roughness parameters in the river bed. They are much easier to provide (e.g. during bathymetric survey of the river bed) than the water stages at flood.

4.1.6 Land use and cover

70 Land-use and land-cover data are mainly used for hydrological and hydraulic modelling. Resources might be available through:

- National statistical bureau: land cover and land-use maps;
- Satellite data: land classification (for global data sets see **Annex 1**);
- Airborne photography: for land-use and land-cover mapping.

4.1.7 Social and socio-economic data

71 Social and socio-economic data are used for the assessment of exposure and vulnerability and finally for the assessment of risks in a given location. Information is available from:

- National statistical bureau: data often aggregated to variable grid size (per km^2, ha) or per administrative unit (county, municipality);
- Satellite information;
- Studies for vulnerability information of communities: requires detailed analysis of built environment, distribution of population, economic activities etc.;
- Insurance companies.

4.2 Assessment and mapping: step-wise tasks and procedures

72 This section explains the various tasks necessary to develop flood maps. There are various approaches to determine flood hydrographs and inundation areas. Their selection depends on the intended accuracy of the maps and the available data and resources. Guidance is needed to select the different methods and to perform them in the most efficient way; in the end an optimum will be accomplished with respect to quality (accuracy) and efficiency. As modelling is an important aspect in flood assessment and mapping, some general considerations are made beforehand.

73 As described in **Chapter 3**, flood risk management is primarily based on five basic maps. These maps are generally prepared in the order of their appearance in the list below: 1) preliminary flood map; 2) event map; 3) hazard map; 4) vulnerability map; 5) risk map. Each flood map can be regarded as a consequence of preceding maps. Various tasks involved in the development of flood maps are provided in **Table 3**.

Table 3 — Overview on the various tasks and procedures of flood mapping

Task	Methods	Developed products
Determination of discharge and hydrographs (4.2.2)	Flood frequency analysis (observed or/and simulated peak discharges); Physically based hydrological model Climate change analysis	**Flood hydrograph** for floods with defined return periods (e.g. 10, 30, 100 and 300 years of return) (with and without effect of climate change)
Determination of flood-prone areas i.e. flood hazard (4.2.3 and 4.2.4)	Geomorphologic approach Historical approach Modelling approach (1- and 2-dimensional numerical models)	**Flood event map** **Hazard maps** for floods with given return periods
Determination of vulnerability (4.2.5)	Micro, medium and macro-scale modelling of tangible assets and mapping of intangible assets within the flood prone area	**Spatial distribution** of population density, assets and goods within the flood-prone areas **Stage-damage-functions** for the assets (based on hazard magnitude) **Vulnerability map**
Determination of risk (potential damage) (4.2.6)	Modelling of the tangible annual probable damage; Modelling of the intangible damages.	**Flood risk maps** showing the spatial distribution of tangible (annual probable damage in value/m^2) and intangible damage.

4.2.1 Today's role of modelling in flood assessment and mapping

74 For decades flood mapping has been based on data of observed and recorded events. Water levels and direct observations have been converted into maps. The assessment of ground features like fluvial deposits provided additional information for the assessment of floods and flood-prone areas. The historic and the geomorphologic approaches are valid methods to determine flooding in a particular area. However, the increase of vulnerability in many places has driven the development of the hydrological knowledge and the request for the possibility to predict the consequences of extreme events. To achieve this objective, the use of mathematical models has been gradually developed and introduced as an essential tool to produce the flood maps. The modelling approach consists of two components:

- the flood hydrograph analysis to define a design flood flow; and
- the routing of the flood hydrograph through the flow domain[5] to delineate the flood-prone area

75 This modelling approach is schematically described in **Figure 21** and discussed briefly in the following sections, together with the other approaches.

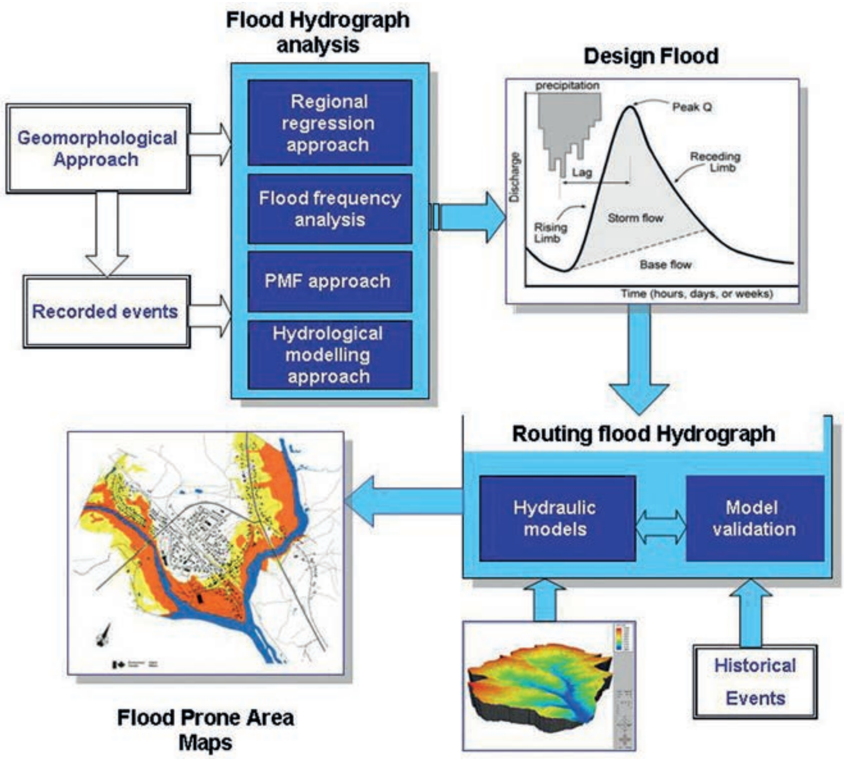


Figure 21 — Modelling approach in flood mapping

4.2.2 Determination of discharge and hydrographs

76 The estimation of flood discharge and hydrograph estimation are most fundamental to flood hazard and risk mapping. The main input data for assessing flood hazards are probability of occurrence (annual return interval, ARI) and the discharge in rivers (m^3/s). The following ARI are

5 Flow Domain: the river reach exposed to flooding: river networks, floodplains, sewage system, etc.

often considered: frequent event (HQ10); rare event (once in a generation; HQ20 to HQ30); very rare event (once in a life time; HQ50 to HQ100); extreme event (HQ300, HQ500 or HQ1000). However, other intervals can be used according to needs.

77 Statistical analyses are used to determine peak discharge for given recurrence intervals if discharge data are available. Techniques for un-gauged areas on global flood and hazard modelling using statistical peak flow estimates are described in (Herold & Mouton 2006; 2011). A method to develop synthetic unit hydrograph **(SCS)** and rational methods in peak flow estimation are given in (Majidi et al. 2012).

78 Today, modelling approaches are widely used to develop flood hydrographs, including peak flow estimation. It is important to include a written technical outline of the work to be performed in the modelling analysis to direct the users to a systematic procedure. An experienced hydrologist must be on the team to execute the various tasks.

79 There are a number of distinct steps involved in determining the magnitude of flood discharge and hydrographs.

- **Step 1.1: Delineation of study area:** The estimation and modelling of the discharge and respective hydrographs of a river preferably requires a whole watershed or sub-watershed boundaries as the study area (eliminates the requirements of upstream boundary inflow).
- **Step 1.2: Selection of modelling approach for discharge simulation:** Flood discharge may be determined directly from data recorded at gauging stations along the river or through the use of a modelling approach (where long-term recorded discharge data are not available). Hydrological rainfall-runoff models (lumped model, distributed models) dominate in the determination of flood discharge and hydrographs.
- **Step 1.3: Data collection and collation for model setup:** After selecting the suitable approach for modelling (lumped rainfall-runoff model or distributed model), the spatial and temporal input data required for model setup and for calibration and verification of the model parameters are to be collected from various sources or organizations responsible for collecting and maintaining those data.
- **Step 1.4: Model validation:** The data to validate the model should include the following:
  - Peak flood discharges developed at gauging stations or computed;
  - Rainfall distribution and total rainfall values;
  - Rainfall and soil moisture conditions before the storm for single-event analysis.
- **Step 1.5: Flood discharge simulation for design storm events:** Following the validation step, the model is ready for exploitation and flood discharge simulation for the design rainfall of selected ARI.

The detailed description is given in **Annex 2**.

4.2.3 Determination of hazards in the flood-prone areas

80 Hazard maps for flood prone areas can be produced in both the preliminary and the detailed stages. Whereas the geomorphic and historic approaches are mainly used for the preliminary assessment, these two approaches also serve as the important basis for a detailed assessment.

In this mapping stage, modelling approaches are often used for accurate flood information. The main aspects of the three approaches are described hereunder:

4.2.3.1 Historic approach

81 The historic approach provides information on known areas that have been inundated in the past by flood waters from rivers and creeks or from the sea. The time range of the past may vary from a few days to several decades (or even centuries). With satellite data the near real-time information is today available.

82 The outline of flooded areas is generated from a puzzle of historical accounts like

- Information from global, regional or national data bases (see **Section 4.1**): most relevant in those data bases are the date of occurrence of the event, affected areas (sometimes with maps or based on satellite imagery) and effects (damage to human beings, assets, infrastructure);
- Written reports (newspaper articles, detailed technical reports, etc.): in general such documents provide information about causes, areas affected, magnitude of the flood. The information is often relevant for the local level;
- Photographs **(Figure 22)**, in limited cases also drawings or paintings and old maps **(Figure 23)**. It is most relevant to determine whether today's conditions are still the same as during the time of the document;
- Archived field data in national archives or libraries (flood assessments, high water marks, design criteria for structural measures etc.). Flood levels in certain reaches/areas **(Figure 24)** may be used for back-calculation of past floods using standard hydraulic models;
- Aerial photographs and in recent years satellite imageries (collected at the time of the actual flood event or through subsequent surveys): this is particularly useful for large areas inundated **(Figure 25)**.

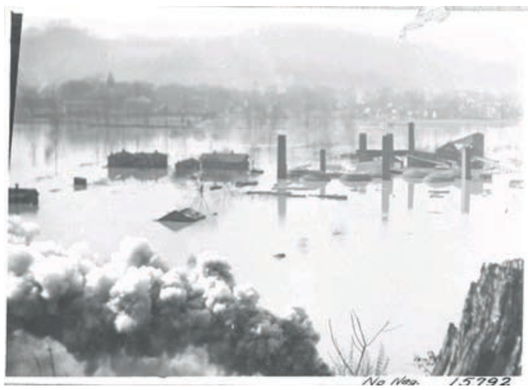


Figure 22 — Historical photograph of Cumberland River flood, 1939, Burnside, Kentucky (US Army Corps of Engineers)

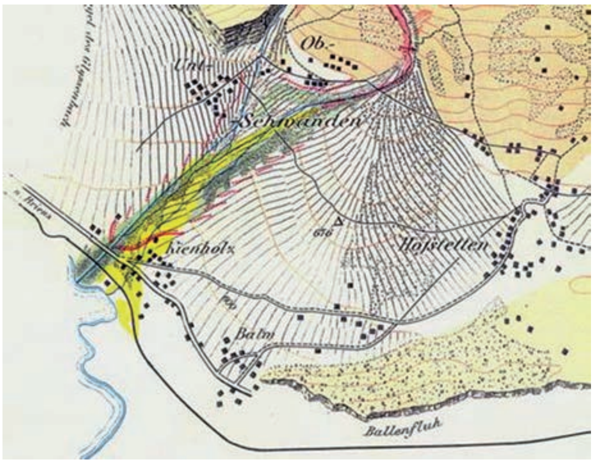


Figure 23 — Historical map by Albert Heim (1897), showing conditions after the major flood and debris flow events of 1896 in the Lammbach (Brienz, Switzerland)

Figure 24 — High flood level of 1905 flash flood event in Khizer River, Gilgit-Balistan, Pakistan (Photo: Markus Zimmermann, August 2006)

Figure 25 — Elbe flood fo 2002 in Germany: satellite images on 14 (top) and 20 (bottom) August (Image courtesy Jacques Descloitres, MODIS Land Rapid Response Team at NASA GSFC)

83 Data for all significant flood events in a given area are collected; the flood map consists of inundated areas of different events, either depicted separately (on different maps or different GIS layers) or overlaid on each other as a single entity. It needs to be updated periodically as

the new information of subsequent events becomes available. The flood event map is used as strong visual reminder that the risk of flooding is very real. In addition, the data that is collected and interpreted with the historical approach is often necessary in the hydro-dynamic approach for the calibration of the hydrological and hydraulic modelling.

84 The Documentation of Mountain Disasters tool **(DOMODIS)** is a systematic approach to assess past disasters (Hübl, 2002). Although it is meant to document recent disasters, it also helps to analyse past events. The focus is placed on mountain disasters, including floods, flash floods, debris flows and similar geomorphic processes.

85 In recent years remote sensing methods (mainly based on satellite imagery) are used to develop flood event maps of the current flood. They are used for emergency response as well as an initial layer for a later flood hazard or risk map. The UNOSAT Humanitarian Rapid Mapping service is operational since 2003. The results of UNOSAT analyses are shared as maps, reports and GIS-ready data layers for direct integration into in-field and headquarter mapping systems. The majority of services are related to hydro-meteorological disasters.

86 The result of detailed historic analyses of various kinds of data is an "event map" showing the extent of one or several flood events. If other information is available, the recurrence interval (or at least a qualitative statement about recurrence, like frequent, rare, very rare) can be attributed to the particular event. Additional information like water depth, flow velocity or similar parameters might be available.

87 It should be noted that conditions in the flood plain or on the alluvial fan might have considerably changed since the occurrence of the past event. A similar flood event in future might have completely different characteristics due to changed landscape (e.g. long embankment with highway might deviate flood waters in another direction).

4.2.3.2 Geomorphologic approach

88 The geomorphic approach, on the one hand, provides independent flood information based on surface features found on the ground and their interpretation. On the other hand, this approach may provide information for events, where peak flows have been observed that exceeded the 100-year flood discharge calculated by regional analysis. These events can often be traced to processes such as debris flow, flood from dam rupture, or glacial lake outbursts (Jakob & Jordan, 2001). Rivers and streams in mountainous regions are especially prone to such large-scale processes and phenomena.

89 The geomorphologic method is based on mapping the geomorphologic evidence associated with a river or stream **(Figures 26 & 27)**. It is based on the analysis of flood plains, alluvial fans, preferential river channels, terraces and other features of erosion and sedimentation phenomena, in particular slack-water deposits. The approach investigates the historical details of the river regime and estimates discharge in paleo-channels.

90 A first analysis includes various sources like remote sensing data, aerial pictures, photographs, geological and geomorphologic field observations and investigations, historical literature or eyewitness reports. The analysis includes the identification and interpretation of all visible morphological features and changes of the river bed. The superposition of this information

enables the creation of a comprehensive geomorphologic map where the evolution of the river can be described and the former geometry of the river bed reconstructed. Field work for this approach is essential, but is time consuming. Therefore, it limits the size of the areas to be assessed and mapped.

91 Recent efforts in dating methods and techniques (Schneuwli et al., 2012) suggest making full use of field data for magnitude-frequency analysis. Dating methods include stratigraphic analysis, radio carbon technique, cosmogenic nuclides, lichenometry, dendrochronology or vegetation analyses. However, some of these methods and techniques are very time-consuming and costly.

Figure 26 — Typical geomorphological features of mud flows of various ages on an alluvial fan Hatoon, Khizer District, Pakistan, 36°16′ N, 73°45′ E (Google Earth, accessed March 2013)

Figure 27 — Active and paleo-channels.
During major flood events such paleo-channels are the first to be inundated or even reactivated.
Near Indus River, Uttar Pradesh, India, 26°26′ N, 79°11 E (Google Earth, accessed March 2013)

92 The geomorphologic approach is used to provide a first assessment of past flood activity, to characterize the magnitude of processes, and to outline the previously flooded areas. However, the results have to be considered as historical data and can't be defined as potential future events without additional investigations. Furthermore it is a starting point for more in-depth investigations and remains a useful resource for a general approach including modelling.

4.2.3.3 Modelling approach

93 The accuracy of flood prone areas and the hydraulic conditions on these areas (water depth and flow velocity) more or less decide on the informative value of the flood hazard map. In general, the records of historical floods are not sufficient to determine the flood prone areas for the whole range of flood events (e.g. 20-, 100-year, and extreme flood). Thus, the application of mathematical models is more or less mandatory for the development of detailed flood hazard maps.

94 Today, hydrodynamic fluvial flow models are widely applied in the engineering business with the availability of high performance personal computers. One- and two-dimensional flow models are, in the meantime, standard applications in the hydraulic design of rivers and flood mitigation measures.

95 For reasons of quality and efficiency the determination of flood prone areas by hydraulic models should strictly follow the following sequence of actions:

- **Step 2.1: Delineation of study area:** The first step in setting up a hydraulic model of the river is to define the upstream and downstream end of the model area.
- **Step 2.2: Selection of modelling approach for fluvial flow simulation:** The main questions to be answered are:
  - the dimension of the model: 1-dimensional, 2-dimensional;
  - the coverage of the flood dynamics: steady or unsteady flow regime;
  - the appropriate flow resistance approach; and
  - the handling of hydraulic jumps and hydraulic structures (bridges, weirs, culverts).
- **Step 2.3: Data collection and collation for model set-up:** Input data of these models are

i Geographic data such as:
  - Topography based on DTM of the ground surface and Aerial images;
  - Land use distribution including wooden vegetation and biotopes; and
  - Bathymetry of river bed; and

ii Hydrological/hydraulic data such as:
  - Stage discharge relationship at the downstream end of the river section;
  - Historic flood data: delineation line of flood; velocities, water surface elevation;
  - Hydrograph of water stage and/or discharge, including peak discharge;
  - Roughness parameters.

- **Step 2.4: Model calibration and validation:** A good calibration result is given if the water depths of the observed flood events are reproduced with an average error of less than +/- 5 cm, assuming reliable observations.
- **Step 2.5: Flow simulation for the flood events:** The results of the flow simulation are the water level and the flow velocities within the river section covered by the model. In case of a 1-dimensional hydraulic model, water level and flow velocities are given as average values within a cross section. For 2-dimensional flow models the results are the spatial distribution of the water depth and the depth-averaged velocity components in the horizontal plane.

– **Step 2.6: Determination of the inundated area:** The final delineation of the inundation area needs the combined use of the DTM of the ground surface and the calculated water levels from **Step 2.5**.

The actions described in detail for each step are given in **Annex 2.2**.

96 Today, a number of hydraulic simulation tools are available to model channel discharge and flooding in flood plains with 1- and 2-dimensional approaches. The Hydrologic Engineering Center River Analysis System **(HEC-RAS)** is available free of charge[6]. Commercial software packages are widely used and distributed, e.g. FLO-2D to simulate floods and flows[7] or the MIKE 11 river modelling tools[8].

4.2.4 Assessment and mapping of debris and mud flow hazards

97 In general, the mapping of debris and mud flow hazards in steep mountainous channels follows the same procedures as for the floods; however, the assessment is less accurate than that of flood hazards. Uncertainties with regard to probability of occurrence are higher, the flow characteristics are less determined and flow behaviour less predictable. Nevertheless, a systematic procedure provides reliable results. In the following paragraphs only some particularities of mud-flow hazard mapping are depicted. Information provided in the sections above for flood mapping is also applicable for mud flows. Additional information is available in (WMO 2011b).

– **Step 3.1: Determination of mud-flow prone watersheds:** The geographical extent of watersheds and channels where mud flows and related processes can occur is much smaller than that of flood processes. The basin size is often only a few square kilometres; in general it is less than 100 sqkm. The determination of mud-flow prone watersheds and channels is based on the availability of erodible sediment sources, availability of water (watershed basin), and steepness of the channel (Rickenmann, 1999).

– **Step 3.2: Definition of design events:** The average recurrence interval (or probability classes) for mud flows is often similar to those used for floods: frequent event, rare event, very rare (or extreme event). For the definition of the magnitude-frequency relations, the historical and geomorphological approaches are applied in combination. Nevertheless, the degree of uncertainty is considerable.

– **Step 3.3: Determination of potentially affected mud flow areas:** For the preliminary assessment it is suggested to use the geomorphologic approach for a limited geographical area (few channels or alluvial fans). The mapping of the fan area as a whole provides first indication of possibly affected areas. For large areas a modelling approach can be envisaged (see e.g. Horton et al., 2013[9]).

6 US Army Corps of Engineers: Hydrologic Engineering Centers River Analysis System (HEC-RAS), available at: http://www.hec.usace.army.mil/software/hec-ras/

7 FLO-2D Software, Inc., products, webinars and training available at: https://www.flo-2d.com

8 DHI Group: MIKE 11 river modelling package and applications, available at: http://www.dhisoftware.com/Products/WaterResources/MIKE11.aspx

9 The modelling tool is available free of charge on www.flow-r.org

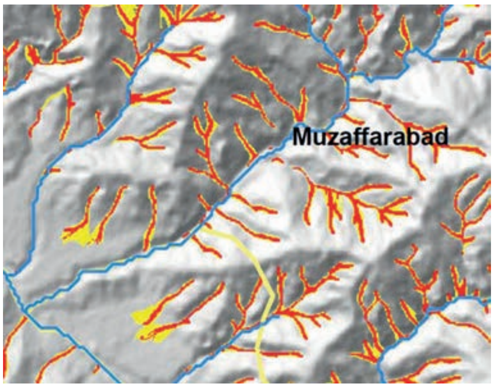


Figure 28 — Debris flow modelling in AJK, Pakistan (Internal project document ERRA, Government of Pakistan)

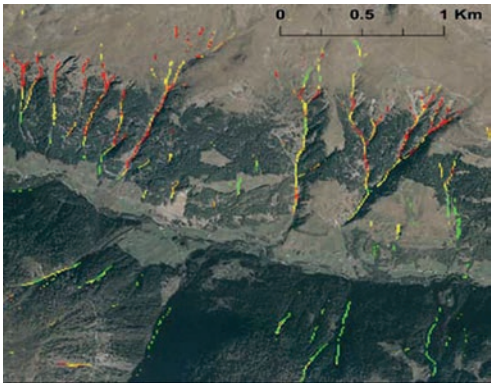


Figure 29 — Debris flow modelling and hazard initiation in Valtellina di Tirano, Italy, using an empirical model (Blahut et al., 2010)

For detailed assessment, the geomorphologic and historic approaches (in combination) provide a good estimate of the potentially affected areas. Hydraulic models exist for the simulation of flow velocity and accumulation depth on the fan, e.g. FLO-2D or RAMMS[10].

4.2.5 Determination of vulnerability

98 Flood mapping concentrates on exposure but includes different susceptibility to particular elements. Exposure includes:

– Population density, indicating also to particular vulnerable groups (e.g. distribution of senior citizens homes);
– Residential area with building stock;
– Lifeline infrastructure like school, hospital, fire guard station, reservoir, telecom station, power transformer and switch yard;
– Traffic infrastructure;
– Industrial estate with indications for environmental relevance (e.g. chemical plants);
– Primary sector territories (agriculture, horticulture, pisciculture etc.)

10 RAMMS Rapid Mass Movement System: Two-dimensional dynamics modeling of rapid mass movements in 3D alpine terrain. Available at: http://ramms.slf.ch/ramms/

99 Vulnerability is a relative size i.e. it describes the degree to which a community or an element is either susceptible or resilient to the impact of a damaging phenomenon. In this meaning it evaluates the extent of possible damage in a given area. This damage is either

- **tangible:** direct damage to buildings, infrastructure, goods and indirect damage due to interruption of economy, shut down of business, etc.;
- **intangible:** life and human suffering, cultural and ecological elements.

100 Intangible vulnerability and damage can only be determined with high uncertainty. Although the number of people affected by flood is derived from the population density within the inundated area, the severity of their exposure can hardly be evaluated. Factors such as water depth and flow velocity are used to assess the risk of casualties, which directly links hazard maps with risk assessment.

101 Three approaches, which differ in scale and resolution, are available to determine and map tangible vulnerability and risk:

- **Micro-scale approach** (community-level) is an object related method based on empirical damage data. This scale is recommendable for small catchments (size has to be defined: several 100 hectares in rural environment to less than 1 hectare in urban areas) or selected areas which require very detailed considerations. This method is based on interviews with people who are/were affected by flood or on real damage data. The (potential) damage can be assessed for each element separately. The micro-scale approach is in general too detailed for flood risk maps. It is primarily used in flood mitigation plans to determine the necessary measures of adaptation at each property as this scale allows precise recommendations for appropriate protection measures.
- **Meso-scale approach** is an area related method. This scale is normally used for larger catchment areas. For the process of risk assessment single land use types (residential area, industrial estate etc.) based on digital geographic data are aggregated to larger, more general ones. The corresponding amount of losses is based on statistical economic values and can be described with the unit €/m^2.
- **Macro-scale approach** is similar to meso-scale, but the data is even less detailed. The area of interest is larger compared to the other approaches (e.g. international river catchments). Sometimes more than one hazardous process is considered.

102 The vulnerability maps show consequences in the flood prone areas in case of inundation. The vulnerability is dependent on the affected values of elements and their susceptibility vis-à-vis the intensity by which they are exposed to floods. In preliminary assessments the macro-scale and meso-scale approaches are recommended for the development of flood vulnerability and risk maps; in detailed assessments it is the micro-scale approach. The flood damage/vulnerability is determined in the following four steps:

- **Step 4.1: Categorization of the land use in standard land-use units:** In macro-scale approaches the land use is taken from geodetic maps which are in general provided by surveying agencies. These maps can vary in spatial resolution and in the refinement of the land-use units. Satellite imagery is another data source. For the macro-scale approach the definition of the following main land-use units is regarded as sufficient:
  - settlement;
  - industry and commerce;

- farming (agricultural/forestry/fishing);
- infrastructure and public areas.

- Step 4.2: Derivation of assets for land-use categories: The monetary value of each main land-use unit can be determined on the basis of the net assets. This includes the cost of construction and of the inventory. Normally the statistical agencies release their material in an aggregated form (e.g. capital stock for the whole country, for each county). This material has to be disaggregated to get the asset for each property or cluster of properties. Some of these values might not be available in developing countries. Here, a rough assumption has to be made for the various land-use units and economic sectors.
- Step 4.3: Map Overlay of land use and inundation probability: Damage is a result of inundation and is a consequence of the affected elements. Thus, the inundation map needs to be overlaid and intersected with the land-use map to derive areas of equal damage. On the basis of Geographical Information Systems (GIS) different themes of graphical map objects can be easily overlaid and their polygons intersected and formed to new objects which share the attributes of the overlaid themes. Damage is strongly dependent on a third geographical parameter, the water depth during flooding. Thus the areas of equal land use and inundation probability need to be further divided into areas with constant water depth. The whole area of damage assessment is subdivided in a grid. The resolution of the grid cells needs to be adjusted to the variability of the topography in which the water depth can be approximated as a constant value. Each grid cell is overlaid with the inundation map and the land-use map to project the attributes of inundation probability and land use category on each grid cell **(Figure 30)**. Damage functions, in this regard, describe the vulnerability of the land-use categories.

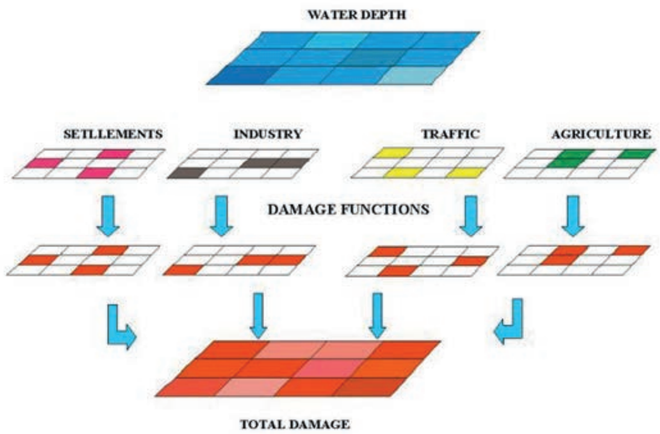


Figure 30 — Applied scheme of map overlay for damage assessment

- Step 4.4: Calculation of the damage on the basis of the capital stock/asset and the damage functions: In case of flooding, the damage will not be total but a percentage of the value of the property. Several sources are available which have determined functions which give this percentage of damage depending on the main land-use categories defined in **Step 4.1** and the maximum local water depth at inundation **(Figure 31)**.

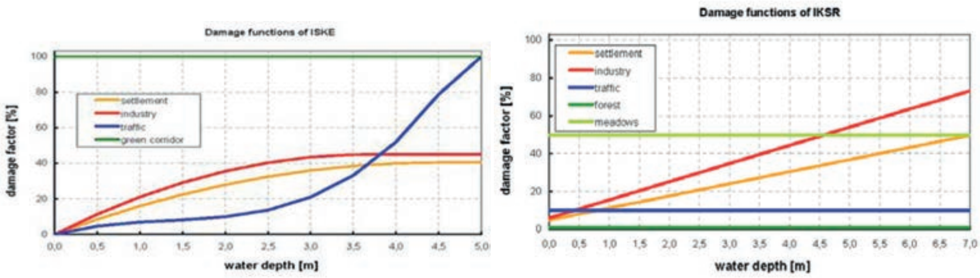


Figure 31 — Damage functions for the Elbe and Rhine rivers (after ICPR and ICPER)

– These damage functions vary considerably indicating that more parameters influence the damage. On the basis of these damage functions the damage within each grid cell determined in **Step 4.4** can be calculated by the following equation:

$$D_{i,j}^{Ln} = C_{i,j}^{Ln} \cdot V^{Ln}$$

103 A general issue is how to incorporate the effect of existing mitigation schemes. A frequent practice is to include the effect of permanent protection works, but not temporary and emergency measures. These measures are necessary, because the area is vulnerable and if damage can be avoided it is a consequence of the action and not of a low vulnerability. The effect may be considered in risk maps since temporary measures reduce probability and thus the risk.

4.2.6 Determination of risk (probable damage)

104 Flood risk is an average value for the probable loss in a given area. One extreme flood event (e.g. a 100-year flood) is not sufficient to assess the flood risk. Frequent floods in particular have a strong effect on the overall flood risk and need to be included in the flood risk assessment although the inundated area and damage at each event is less than at extreme events. Thus risk assessment methods for flood risk need to include the damage of all probable flood events. However, the occurrence of a flood is uncertain and consequently the total flood damage is not a deterministic but a statistical value. It needs to include the probability in the damage assessment[11]. All probable flood events which can occur within a certain period of time need to be considered. Its duration is set equivalent to a return period of a flood which is in general regarded as a risk and taken for the design of flood defence measures. With these assumptions and statistical approaches the method gives probable annual flood damage:

$$\sum_{i=1}^{max} \frac{S(p_{i-1}) + S(p_i)}{2} \cdot \Delta P_i$$

where

- S = damage at a flood event of a certain probability p,
- Δpi = the difference of probability between the flood event i-1 and i, and
- max = the maximum number of flood events to be considered for damage assessment.

11 See an example flood risk estimation and damage mapping in (Arrighi et al. 2013).

4.3 Layout of maps

105 Most text in this section has been taken (and slightly adapted) from the Handbook on good practices for flood mapping in Europe (EXCIMAP, 2007a).

4.3.1 Formal aspects

106 The layout of a flood map, whether preliminary or detailed, whether basic or applied, is as important as the map's content. The formal aspects need to be pertinent to the user, help to ensure that the content of the maps is correctly understood and that the maps convey the relevant flood information to their users, thus achieving the objectives for which they have been produced. The following basic and explanatory aspects are relevant:

- Title: brief description of the map, including its content and / or purpose (for flood maps particularly important are the considered probabilities or recurrence intervals);
- Responsible authority (organisation responsible for the development and publishing of the maps, with contact details);
- Date of preparation / publication;
- Legend (textual description of symbols, colours, point, line, area features, etc.);
- Purpose and method of development and intended use;
- Limitations of map and / or assessment of uncertainty (if available);
- Disclaimer (to enforce explanatory information and limitations, and provide legal protection to the responsible authority against adverse consequences of misuse).

107 The scope and detail of the explanatory information should be appropriate for the intended audience:

- Maps intended for public use should be simple and self-explanatory and include a clear legend, such that as little supporting or explanatory information as possible is required for correct interpretation;
- Maps intended for organisational users (governments, local authorities, etc.) will generally be used by professionals to inform decision makers that may potentially have significant impacts, and will often contain more explanatory information to help the user to fully understand the development and limitations of the maps, particularly in relation to methods of development, limitations and uncertainty.

4.3.2 Navigation

108 An indication of orientation (direction of North bearing) and map scale are required for correct interpretation. Scale information may be provided as:

- A written scale (e.g., 1:10 000) in the title box or legend together with scale bar provided on the map; this allows easy change in paper size;
- Grid squares provided on the map (with the grid square size defined in legend).

109 A location plan is frequently used alongside the main map to help users identify the geographical location that the flood map represents. This plan shows the coverage and the location of the map within a wider geographical area (e.g., country, region or river basin).

110 Special navigation tools will be required for internet-based maps to enable users find an area of interest. Tools often include zooming (in and out) and panning and can include relocation from a location plan (as described above) or a return to default view (e.g., regional or national scale view).

4.3.3 GIS-based map use and dissemination

111 Appropriate meta-data should be provided where maps are issued or downloadable in GIS format (e.g. shape, ascii). Such data should include standard meta-data (dates, responsible organisation, etc.) as well as information necessary for use of the GIS data, including the map projection and any datum levels used. Consideration should also be given to any relevant meta-data protocols or requirements.

4.3.4 Background imagery

112 Proper background is necessary to provide geographical reference for the flood information. Particularly important for dissemination of map information: the users need to relate to known geographical conditions. The background imagery should not be too dominant, in order not to confuse with symbols or colours of the flood information.

Today several products can be used as background imagery:

- **Topographic maps showing terrain** with contours, rivers and other water bodies, forests, built environment etc. are normally used as background imagery. The use of light grey or black-and-white is often more favourable than a coloured map. Caution: topographic maps are hardly available in many countries, do not have an appropriate scale or are outdated;
- **Aerial photographs** (often ortho-rectified) build a good base for detailed flood maps;
- **Satellite imagery** may give a detailed view, but are often expensive;
- **Google Earth** is an appropriate, widely used and powerful tool to provide detailed background information when flood information is overlaid.

4.3.5 Colour palettes and symbols

113 Simple flood maps may show only a single flood parameter (such as the flood extent for one flood frequency or return period) using a single coloured layer over a background map. The use of different colours (or shades of a single colour) may be used to present multiple parameters (such as flood extent for multiple frequencies, flood depths within a given extent, or classes of flood hazard or risk) in a clear and comprehensible format.

114 The choice of colour coding may be guided by a number of factors:

- Social conditioning: People are conditioned to interpret information based on colour, e.g., blue may be taken to represent flood extent, and red, yellow and green are taken to represent danger, caution and safety, respectively (traffic light);

- Graduations of colour: Graduations of colour may be used to represent different degrees of a single parameter. The graduation may be discrete or continuous;
- Black and White Reproduction: The possible reproduction of a colour map in black.and-white might be considered in choosing a colour scheme, noting that different colours may appear as the same shade of grey once copied;
- Clarity: Strong colours may be used to provide clarity over a coloured background map, although it might be noted that an excessive number of strong colours can make a map difficult to interpret.

115 Hatching may be used as an alternative to different shades or colours in representing different parameters. The use of different line types that bound a polygon or flood extent provides another opportunity for differentiation.

4.3.6 Numerical flood data

116 Flood maps represent information graphically. This visualisation can be supplemented with numerical data, such as values of water level or flow, either directly as text on the map or in a table on the legend. Such data can also be provided as attributes or tables associated with the flood maps where the maps are issued or downloadable in digital GIS format.

5 DISSEMINATION OF FLOOD INFORMATION

117 Flood management is based on sound technical assessments. However, the results of these assessments remain useless if the information cannot be properly disseminated to the responsible agencies and to the involved population and finally, if the information cannot be translated into the respective measures. Moreover, people's perception of a specific risk often determines on the acceptance of such measures. Therefore, it is of utmost importance to use appropriate communication channels to disseminate and translate assessment results, represented on maps, into specific actions on the ground be it on local (community) level, national or regional (trans-boundary) level. This process is well represented, e.g. in the RiskMAP lifecycle, elaborated by FEMA (WMO, 2010). The receiving party for the risk mitigation, whether they be local or national government agencies, trans-boundary river bureaus, NGOs or the concerned public (i.e. all involved stakeholders), require the necessary awareness for flood risks and need to understand the flood information to prevent or mitigate the respective risks or prepare for the flood.

Figure 32 — Risk map lifecycle: risk mapping, assessment, and planning (FEMA, 2009a)

118 This chapter will briefly outline issues of awareness raising, the dissemination process and the interpretation and implementation of the given information.

5.1 Risk awareness

119 Public awareness for and education in flood risk are key elements for flood management in flood prone areas. A high level of awareness for flood-related risks is required to have effective and efficient flood risk reduction measures; e.g. successful evacuations require awareness and planning among the population of what to do and where to go in a flood emergency (WMO, 2009).

120 Properly presented, flood maps allow residents to see exactly where and how they may be impacted by floodwaters. In addition, maps help to understand the process of flooding and are needed to provide information to guide people's behaviour in case of the event. People, residing in an area where flooding is a frequent event, have devised (out of experience), many ways of coping with them. There are numerous examples which show that the losses are quite lower in frequently flooded areas where people are aware of the risks.

121 According to (WMO 2011a) "awareness can be raised through education and regular training – particularly in areas exposed to infrequent hazards or within new settlements. Flood hazard maps, depicting flood-prone areas, evacuation routes and safe shelters, can play a critical role in awareness building. Women and children should be included in education strategies, as they are disproportionately affected by natural disasters. Outreach efforts should be made to minorities and ethnic groups, as their mobility may be limited or affected owing to cultural, social or economic constraints".

122 The awareness programme should be designed carefully and judiciously. Over emphasis on physical science and technical explanation, sensationalism of damage and destruction and over emphasis of emergency response may sometimes hamper the awareness idea. On the other hand, personalization of risk, emphasis on effective risk reduction strategies and building

self-confidence may enhance the awareness process. The effective risk awareness and risk reduction education programme should be based on

- **Who:** target groups like; public, policy maker, knowledge disseminators etc.;
- **What:** like; clear and consistent message, non-technical language, positive empowering and accurate examples, strong emphasis on risk reduction; and
- **How:** like engaging innovative formats, employing a multiplicity of dissemination strategies.

123 Further, specific awareness programmes are to be formulated at various levels. There should be separate and adequately detailed guidelines at national and regional levels depending upon the needs. The awareness programme should promote cross-sector collaboration, encourage community participation and grassroots initiatives. It may be included in the compulsory education and should always be improved upon through assessment and evaluation (such as Risk RED[12]). Nowadays, many organizations implement community-based disaster risk management approaches; where the awareness-building component has a high profile (WMO, 2013; IFRC, 2000).

5.2 Means of communication

124 The communication of flood hazard and risk is a complex cross-disciplinary field where different audiences need to be reached. In most cases flood maps are used to communicate the relevant information to these audiences. Generally, means of communication are tools or devices to transit information to a target audience conceived as a single unit or a number of individuals **(Figure 33)**.

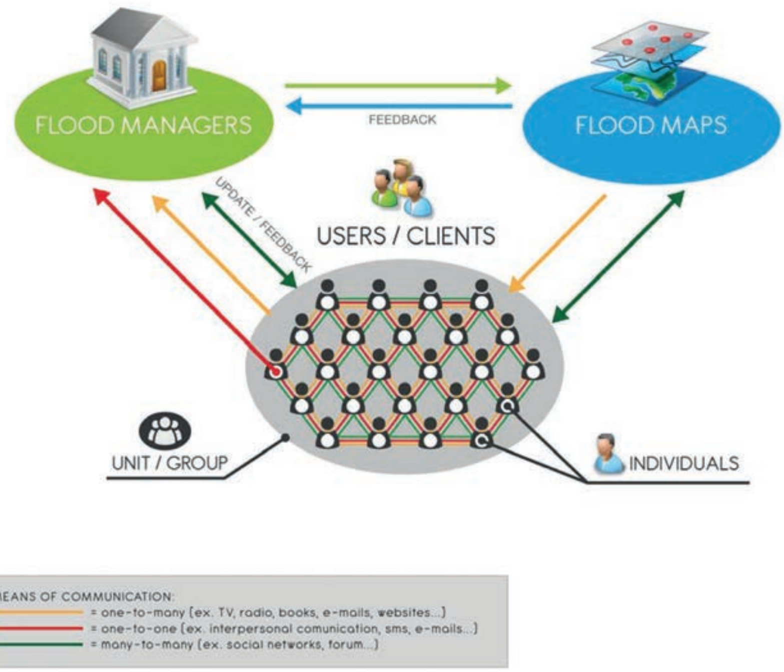


Figure 33 — Means of communication in delivering flood maps

12 Risk RED is a non-profit organization that seeks to increase the effectiveness and impact of disaster risk reduction education. Further information at: http://www.riskred.org/

125 Flood maps, in this regard, serve as a mean of communication to address both a group and an individual. They can be categorized according to their type and form, which in turn depend on the stakeholder's needs and priorities:

- Conventional maps on paper (hard copy) are mainly used for technical meetings, for the land-use planners, in development agencies or emergency services. In general, the local level is addressed;
- Digital maps are freely accessible for the public or built into a national data-base (GIS portal). This can be found e.g. in the UK, where the Environment Agency provides a nation-wide service to communicate flood risks and flood alerts (EA, 2013). Electronic maps are used by national or local planning agencies, emergency services or, if there are enough details, for the potentially flood-affected population;
- Static maps (posters, paints etc.) can be displayed in a public space, at community gatherings or during awareness building campaigns;
- Dynamic flood maps display the required scenario on the map on a real-time basis or at certain time intervals. This information, in an advanced stage, might be used by emergency managers or rescue services. Properly developed, it might also be used to inform the population at risk; however this is only advisable when clear emergency procedures for those groups are known. Particular care is necessary in trans-boundary conditions, where different publication policies, hazard and risk classes, or colour schemes may prevail.

126 A completely different way of communicating flood hazards are colour-coded flood poles to define particular flood heights (water depths) in very specific locations **(Figure 34)**. Normally the colour code would call for distinct actions if a particular flood level is reached or exceeded.

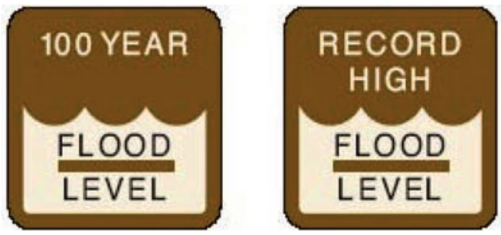


Figure 34 — Flood level marks (U.S. Forest Service)

127 The responsibility of the release of flood information within or after a flood mapping programme resides with the Flood Mapping Committee. Unless information is conflicting, multiple communication means can be used to deliver information in any stage, e.g. emergencies, normal time, programme planning or implementation phases. In some cases, instantaneous demonstration of flood maps is useful, e.g. during TV and radio broadcast either for advisories or educational programmes.

128 All means of communication should allow for feedback. Very often, the users have either rather general or very specific questions. It might also be that a local person has special information not known to the technical planning team. The dissemination procedure should foresee such feedback loops.

5.3 Interpretation and implementation of flood information

129 Stakeholders need to understand the basic elements of flood risks and the possibility to reduce those risks. This requires knowledge about the various parameters of hazards, i.e. extent, flow depth or flow velocity for a given recurrence interval, about exposure and vulnerability (susceptibility) and about the interplay of these elements to form the risk (see **Section 2.1**). The interpretation of the information in the available flood maps is hardly possible without this basic knowledge.

130 The effective transfer and interpretation of flood related information to the public is decisive for the success of the participatory approach and is one of the central tasks related to flood risk management. Different strategies should be adopted in order to analyse and/or to evoke risk perception and risk awareness (see **Section 5.1**). Some of these initiatives should be developed following the aim to generate interactivity and knowledge exchange between experts and map users (authorities, the involved local population). Others are simply based on a more common approach while confronting different target groups with knowledge, tools & toys and/or experiences.

131 The UK Environmental Agency uses very straight-forward guidance on how to interpret the respective maps (EA, 2013); the guidance refers to flood extent with a particular probability (100 years, 1000 years flooding), using shades of blue. In this regard it is also important to interpret areas without colours. For the UK case it says: "Clear shows the area where flooding from rivers and the sea is very unlikely. There is less than a 0.1 per cent (1 in 1000) chance of flooding occurring each year."

132 The proper interpretation of the map content and the subsequent implementation of the information into risk reduction measures are highly relevant for the professional users of the map. In particular, land-use planners need to be aware of the main parameters of hazard (extent, magnitude, probability) in order to decide on economic development in flood-prone areas (WMO, 2008b). A particular land use might be prohibited, restricted or conditional, depending on the magnitude or probability the prevailing hazard (see e.g. example of hazard zoning, **Section 3.3**). On the other hand, certain risk levels will call for remedial structural or non-structural measures.

133 In general, for practitioners the following points are relevant:

- **Physical relevance:** water depth or flow velocities are distinct values; they can be implemented according to requirements. On the other hand, the damage factor describing the vulnerability of particular land-use categories is a generalized parameter which might not be "correct" for an individual structure;
- **Accuracy:** flood maps which have been established on a small scale (e.g. 1:10,000 or smaller) show flood hazard or vulnerability parameters with limited spatial accuracy. The interpretation requires special care, particularly for digital products where the user can zoom in. The background image might be in much better resolution than the mapped flood parameter;
- **Limitations:** almost every parameter is shown with an extent having a clear boundary. However, in nature the boundary is often an array with gradual changes.

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ANNEX 1: SOURCES OF TOPOGRAPHICAL DATA

Additional data on global level can be found on the following websites:

Land use and land cover (soil/geology/land-use data)

European + global soil maps	EC- JRC	eusoils.jrc.ec.europa.eu/
European Corine landcover - CLC2000	EEA – EC	Environmental data, charts, maps, indicators and interactive data applications – comprehensive land cover database for European countries and North African countries, original scale of 1: 100 000. www.eea.europa.eu/themes/landuse/interactive
Global Land Cover 2000	EC- JRC	Global Land Cover 2000 Project:; Global harmonized land cover database for environmental assessment. bioval.jrc.ec.europa.eu/products/glc2000/glc2000.php
Global land cover	National Snow and Ice Data Center (NSIDC)	Scientific data sets for research, focusing on the cryosphere and its interactions. Data are from satellites and field observations. nsidc.org/data/
Global Land use & Environmental Data	UNEP & GEO	Environmental Data Explorer: online database with over 500 variables, as national, subregional, regional and global statistics or as geospatial data sets (maps), covering themes like freshwater, population, forests, emissions, climate, disasters, health and GDP. geodata.grid.unep.ch/
Global Geology	OneGeology	Global interactive geology map. portal.onegeology.org/
Global shoreline	NOAA	Information on digital coastline and shorelines data. www.ngdc.noaa.gov/mgg/shorelines/gshhs.html
Land Use Maps, Soil Maps	WaterBase	www.waterbase.org/download_data.html
World Soil Database	FAO & LUC	Global harmonized world database, with supplementary data on terrain, land cover and soil quality. www.fao.org/nr/land/soils/harmonized-world-soil-database/en/
Global Irrigated Area Map	International Water Management Institute (IWMI)	Global satellite sensor based web maps and statistics on irrigated and rainfed crop areas www.iwmigiam.org

Global Ecosystems Datasets	World Resources Institute	Charts and maps of human impact, human in ecosystems, freshwater, grasslands, coasts, forests, agriculture, aquaculture; and Climate Analysis Indicators Tools. www.wri.org/charts-maps/ecosystems
Conservation and ecosystem datasets	WWF	Global terrestrial, Ecosystem and Freshwater Ecoregions Datasets: marine ecoregions, freshwater ecoregions, terrestrial ecoregions, hydrographic information (hydrosheds), Global 200 ecosystems. global lakes and wetlands database. worldwildlife.org/pages/conservation-science-data-and-tools

Elevation and terrain data (DTM = Ditigal Terrain Model)

Global DTM-SRTM3	NASA / USGS	Applicable for preliminary mapping, particularly in hilly areas; less useful in large flood plains. Global coverage; vertical resolution 90m with vertical interval of 1m. www2.jpl.nasa.gov/srtm/
Global DTM-ASTER –Terra	NASA / USGS	Applicable for preliminary mapping; limited use for detailed mapping. Global coverage; vertical resolution 30m glovis.usgs.gov/
DTM	LiDAR	Light Detection An Ranging: optical remote sensing technology; very accurate, but expensive; very applicable for detailed mapping Resolution: horizontal 2x2m, vertical <0.1m. lidar.cr.usgs.gov/
Local DTM	Field survey	Field surveys: accurate, though rather expensive. Applicable for detailed mapping.
Regional DTM	Photo interpretation	Digital orthophoto. Applicable for preliminary assessment, in limited cases also for detailed assessment
National / Regional DTM	Isoline maps	Digitized isolines from topographic maps or scanned and vectorized topographic maps at 300 dpi+ Cheap, applicability limited in large flood plains but provides good results on alluvial fans.
Global Multi-Resolution Topography	Marine Geoscience Data System	Synthesis and Global Elevation Data: multi-resolutional compilation of edited multibeam sonar data merged into a single continuously updated compilation of global elevation data. www.marine-geo.org/portals/gmrt/
Terrain Data (various)	Natural Earth	Public domain map dataset available at scales of 1:10m, 1:50m, and 1:110m, featuring vector and raster data. Themes cover cultural, physical, and raster categories for each scale. www.naturalearthdata.com

Global terrestrial imagery	(various)	Google Earth Bing Maps 3D www.google.com www.bing.com/maps/
High Resolution Topography Data	OpenTopography (U.S.)	A Portal to High-Resolution Topography Data and Tools (LiDAR) www.opentopography.org

Human Data: Population and Statistics

Global 3D city models	Google Earth with 3D objects	In flood situation or simulations the 3D representation allows determining to which degree buildings are affected. This information is useful for the planning of evacuation and for damage assessment.
Gridded Population of World (GPW)	NASA	Global spatial population data at the scale and extent to demonstrate the spatial relationship of human populations and the environment; available in grid or raster format. sedac.ciesin.columbia.edu/data/collection/gpw-v3
Global Population Statistics and Geopolitical Data	GeoHive	Tabulated population statistics: current, historical, estimates, projections, cities, agglomerations, etc. Geopolitical data: global administrative divisions of countries (provinces, counties and such) www.geohive.com

Climate Data

GIS Climate Change Scenarios	NCAR	National Centre for Atmospheric Research: Climate change projections and 2D variables from modeled projected climate for the atmosphere and land surface gisclimatechange.ucar.edu/
Climate Data Library	IRI/LDEO	Earth Institute and Lamont-Doherty Earth Observatory: over 300 datasets from a variety of earth science disciplines and climate-related topics in commonly-used formats, incl. GIS-compatible format iridl.ldeo.columbia.edu/

ANNEX 2:
PEAK FLOW ESTIMATION AND STEP-WISE PROCEDURE FOR DISCHARGE ESTIMATION AND MODELLING

2.1 Flood discharge estimation

There are various methods and approaches for estimating flood discharge information for different ARI flood events. The existing methods can be divided into the following categories:

A) Geomorphologic / historic approach

B) Regional regression approach

C) Flood frequency analysis

D) PMF approach

E) Hydrological modelling approach

The methods A) to C) are based on observations and measurements realized in rivers. The approaches developed in D) and E) are based on hydrological modelling.

A | Geomorphologic / historic approach

In areas where gauging data records are scarce, and/or when the data series are short or interrupted, the following aspects can be used as complementary tools aiding conventional hydrological and flood frequency analysis methods:

- geomorphologic interpretation of the physical environment, in particular using slack-water deposits,
- dating of fluvial deposits and flooding episodes and
- hydraulic reconstruction of past flood events

Catchment geomorphology plays a central role in predicting the nature of the hydrological response. This method can also be used as a preliminary assessment before a more sophisticated modelling approach is initiated.

Discharge, in particular bankfull discharge (Q_{bf}), can be calculated with a simple steady state hydraulic equation based on a paleo-channel's bankfull cross-sectional area and an estimate of the average velocity (see **Box 1**). The method can be extended to estimate the sediment transport in order to evaluate the magnitude of the erosion/deposition processes. The approach provides maximum bankfull discharge from Holocene period. Of course the results have to be used carefully because modern discharges may be affected by human activity and also could be climatically controlled.

Box 1: Discharge equation

The steady-state hydraulic equation is used to calculate (peak) discharge in a given river reach:

$$Q = v*A$$

where

Q = discharge [m^3/s],which is the product of

A = the river cross-section area [m^2], and

v = mean velocity [m/s] of the water flow.

The mean velocity can be estimated; or it can be calculated using for instance the Manning equation:

$$V = 1/n * R2/3 * S1/2$$

where

R = hydraulic radius (cross-section area / wetted perimeter),

S = gradient of river;

n = Manning's roughness coefficient (coefficient varies between 0.02 and 0.07 for natural channels).

B | Regional regression approach

When discharge measurements are not available for a specific location in the watershed, the regional regression approach is used for estimating design flood discharge at this particular location using established regional regression equations. The regional regression equations are developed by relating flood discharges (such as the 100-year flood discharge), to watershed characteristics (size, shape, steepness) and climatic conditions at places where discharge measurements are available (gauging station). For application at an un-gauged site, one must determine the applicable watershed and climatic characteristics. Rainfall-runoff models are often based on a design storm where rainfall amounts are taken from a rainfall atlas, and a time distribution is assumed. These two different approaches can provide widely differing estimates of the design discharge.

Box 2: Regional regression analysis

The regional regression approach is used for estimating design flood discharge at this particular location:

$$Q_T = aA^b SH^c SL^d$$

where

Q_T = T-year discharge [m^3/s],

A = contributing drainage area [km^2],

SH = basin-shape factor defined as the ratio of main channel length squared to contributing drainage area [km^2/km^2],

SL = mean channel slope defined as the ratio of headwater elevation of longest channel minus main channel elevation at site to main channel length [m/m].

Note: This differs from previous rural regression equations in which slope was defined between points 10 and 85 percent of the distance along the main channel from the outfall to the basin divide.

a, b, c, d = multiple linear regression coefficients dependent on region number and frequency

Find further information at Texas Department of Transportation (2011).

C | Flood frequency analysis

Flood frequency analysis enables the magnitude of floods of selected ARI to be estimated by statistical analysis of recorded historical floods. Flood-frequency analysis is used to predict design floods for particular sites along a river. The technique involves the use of observed annual peak flow data to calculate statistical information such as mean values, standard deviations, skewness, and recurrence intervals. These statistical data are then used to construct frequency distributions, which are graphs and tables that tell the likelihood of various discharges as a function of recurrence interval or exceedance probability (Figure 35). Flood frequency distributions can take on many forms according to the equations used to carry out the statistical analyses. Four of the common forms are:

- Normal Distribution;
- Log-Normal Distribution;
- Gumbel Distribution;
- Pearson Type III Distribution.

Each distribution can be used to predict design floods; however, there are advantages and disadvantages of each technique. In recent decades, as a way to solve the problem of lack of information, non-systematic data has been included in flood frequency analysis, with good results. Non-systematic information is the censored information registered previously to the systematic record. There are two sources of information: historical and paleo-flood reconstruction. From the statistical point of view, both sources can be treated equally.

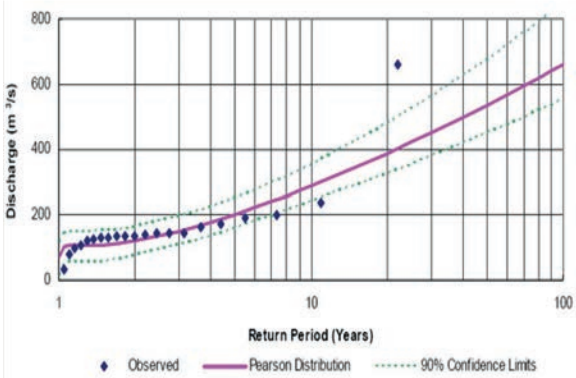


Figure 35 — Peak flow for various ARI at a given location, including range of uncertainty (Kokelj, 2003)

D | Probable maximum flood approach

The Probable Maximum Flood **(PMF)** is the flood due the Probable Maximum Precipitation **(PMP)**. The PMP is the greatest depth (amount) of precipitation, for a given storm duration, that is theoretically possible for a particular area and geographic location. PMF may be expected from most severe combination of critical meteorological and hydrologic conditions that are reasonably possible in a particular drainage area. As such the PMF has a physical meaning. Both, meteorological methods and historical records are used to determine the greatest amount of precipitation which is theoretically possible within a region. The historical data consists of point precipitation amounts measured at rain gages throughout the region being studied, or a region with very similar meteorological and topographic characteristics. These rainfall data are subsequently maximized through "moisture maximization" and other numerical methods. Moisture maximization is a process in which the maximum possible atmospheric moisture for a region is applied to rainfall data from a historic storm. This process increases the rainfall depths, bringing them closer to their potential maximum.

Basically there are two ways to estimate the PMF:

- **PMP estimate using rainfall-runoff models:** this involves many assumptions about the PMP, about the conditions of the catchment and physical features for its upper boundary;
- **Empirical estimate:** The rule of thumb which estimates the PMF or the PMP by a particular and high return period quantile cannot be considered as a scientific method. Although PMF is a direct result of PMP, drainage areas with the same PMP may have different PMFs.

From the PMF point of view, traditional flood frequency analysis has two main drawbacks. First, the lack of information about large events in the systematic record, which involves extrapolating to quantiles of very large return periods from runs of data which rarely exceed 100 years. And second, most of the extreme distribution functions used in hydrology don't have an upper limit.

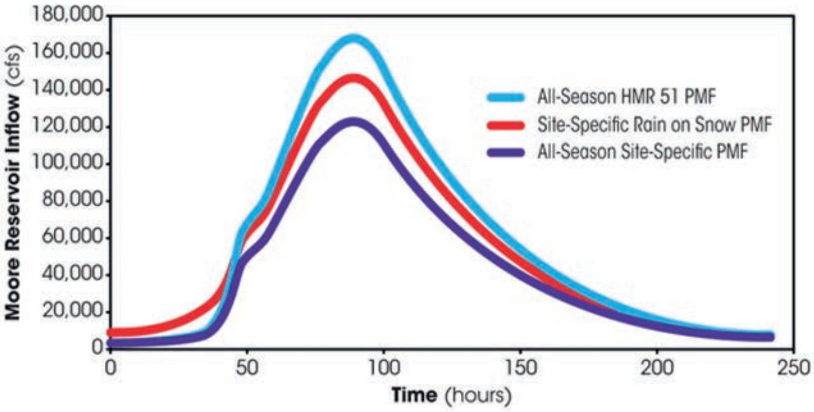


Figure 36 — Probable Maximum Flood hydrograph To Moore Reservoir

Figure 36 compares the inflow probable maximum flood **(PMF)** hydrograph to Moore Reservoir produced from model runs for the Hydro-meteorological Report **(HMR)** 51 probable maximum precipitation **(PMP)** and the site-specific all-season PMP and the site-specific all-season PMP and seasonal PMP on snow (Gomez et al., 2011).

E | Hydrological modelling approach

The aim of the hydrological modelling is to reproduce the land phase of the water cycle and to be able to simulate a variety of events - like flood discharges - in order to understand the dynamic and the spatial extend of the phenomena. This type of tool is useful when a specific event associated to a return period has to be simulated or when measurements are not available.

The amount of flood discharge which results from a given rainfall amount depends upon the characteristics of the drainage basin. Some important characteristics include soil type, land use, size and shape of the watershed, and average watershed slope. Both, the volume and rate of runoff are affected. For example, water will run off more quickly from steep slopes than from gentle ones. Hydrological rainfall run-off models, are categorized as lumped (they consider the catchment area as a single unit) or distributed (they represent the catchment as a system of interrelated subsystems, both horizontally and vertically).

Lumped rainfall-runoff model

The unit hydrograph model (Sherman, 1932) and the simplistic infiltration approach (Horton, 1933) are still today the theoretical basis of the conceptual models in which the catchment is regarded as a system where input (precipitation) is transferred to a runoff hydrograph at the outlet of the catchment by a system function (unit hydrograph). These rainfall-runoff models are "lumped models" and represent the easiest tools to apply with a minimum set of data on the catchment. In most of the cases, the outputs of the models provide an estimate of the discharges at a single point but can't describe the physical processes taking place for each area in the catchment.

Distributed hydrological model

The deterministic approach has been extended to the runoff process including the soil interactions with the physically distributed hydrological models (Beven, 1985, Abbott et al., 1986a & 1986b). Parallel to the development of the distributed models the lumped models have been further refined and improved to more physically based models which fully cover the whole hydrological cycle of land-bound water movement and refine its spatial resolution by sub-catchments and hydrotopes[13]. Most of these models use simple methods such as the SCS method to determine the infiltration rate of precipitation into the ground. The explicit consideration of the various factors that are thought to affect flood runoff makes the method attractive.

The overall trend in rainfall-runoff modelling is directed towards more refined physically based modelling. The lumped and distributed models are increasingly approaching each other. Still the important amount of computing time is one of the major drawbacks of a distributed model. The main interest for the physically based approach is the capacity of the modelling system to be applied on ungauged catchments and to produce specific requested hydrographs from limited amounts of hydrological data.

2.2 Step-wise procedure for discharge estimation and modelling

Step 1.1: Delineation of study area

The estimation and modelling of the discharge and respective hydrographs of a river preferably requires a watershed or sub-watershed boundaries as study area. A proper basin eliminates the requirements of upstream boundary inflow data for modelling, which are often difficult to obtain. A field reconnaissance survey is useful to understand the hydro-geological and socio-economic characteristics of the study area and to gain knowledge of the river systems and floodplains, status of hydro-meteorological gauging stations and history of floods and their impacts. Some of this information is very important in deciding most suitable modelling approach for flood discharge simulation.

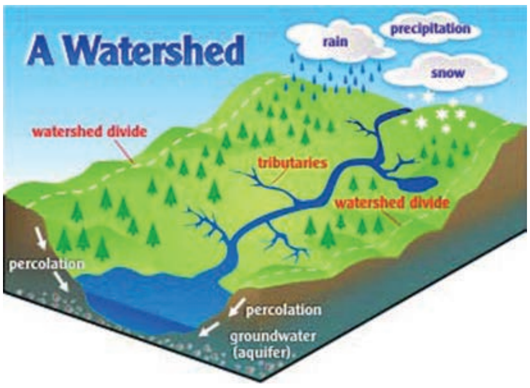


Figure 37 — Study area, in general a watershed or catchment, to determine discharge (Sandusky River Watershed Coalition)

Specialists have to be aware that administrative boundaries of any area or region often don't coincide with hydrological basin boundaries; this sometime leads to difficulty in delineating an appropriate study area boundary suitable for modelling the discharge.

13 Hydrotopes are areas of equal hydrological characteristic with respect to the vertical processes of interception, infiltration, evapotranspiration and groundwater recharge.

Step 1.2: Selection of modelling approach for discharge simulation

Flood discharge may be determined directly from data recorded at gauging stations along the river. Preferably, records are going back several decades. In addition, they may be estimated based on long-term data from gauges in nearby areas having similar characteristics. A modelling approach is required to simulate design floods especially where long-term recorded discharge data are not available. Hydrological rainfall-runoff models (lumped model, distributed models) dominate in the determination of flood discharge and hydrographs.

Flood discharge is determined using

- i **Gauged data** from stations along the river (flood frequency analysis); if data are not available or data series are too short or unreliable;
- ii **Gauged data** from stations in nearby areas (for regional regression analysis) and/or;
- iii **Modelling approach:** Several hydrological modelling approaches are available;
- iv **Geomorphologic approach** provides additional information about flood frequency and magnitude in a specific river reach (particularly for extreme stages and discharges).

Step 1.3: Data collection and collation for model set-up

Data needs for modelling vary, depending on the method or approach to be employed. After selecting the suitable approach for modelling (lumped rainfall-runoff model or distributed model), the spatial and temporal input data required for model setup and for calibration and verification of the model parameters are to be collected from various sources or organizations responsible for collecting and maintaining those data. It is important to know how the data can be obtained or developed. Some of the data from surrounding areas of the watershed may be useful such as rainfall, etc. and some datasets can be obtained from regional or global databases. Relevant data are:

- Daily and hourly rainfall data for the watershed and surrounding areas;
- Watershed area, stream length and contributing area;
- Soil characteristics and vegetation cover (to estimate infiltration conditions);
- Discharge data (for model validation);

Data Validation: Gauged rainfall data should be obtained and rainfall maps prepared using the Thiessen or isohyetal techniques **(Figure 38)**. Either of these techniques may be used to estimate the average storm rainfall on a watershed. If discharge gauges are available, the recorded flood events should be obtained from the agency in charge or from a reliable website. If several actual storm-flood events are available, all should be used in the validation process.

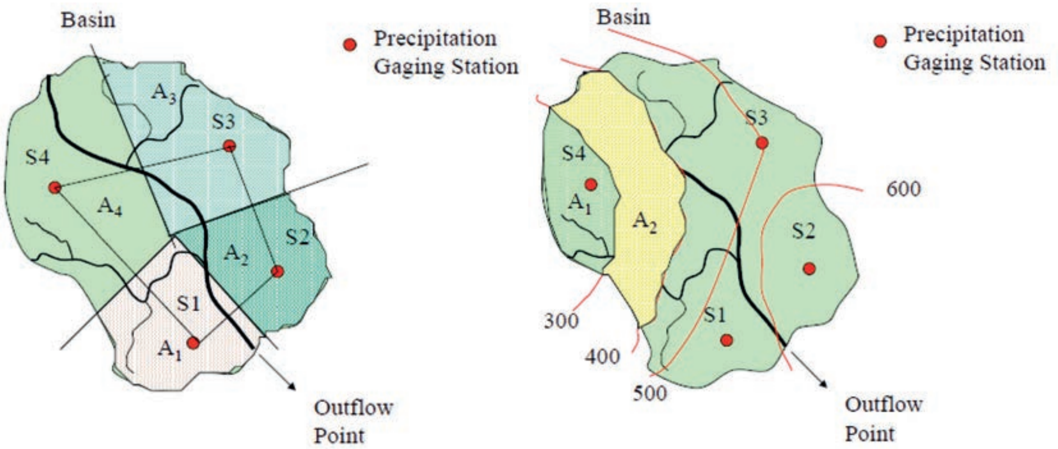


Figure 38 — Estimating average areal rainfall over watershed
using Thiessen polygon (left) or isohyetal methods (right) (Nicholas School of the Environment)

Data from different sources are available in different formats and resolutions. It is important to convert those data to required formats for the selected model; they should be analysed for consistency and missing values.

Step 1.4: Model validation

Every model needs to be validated before it can be applied for simulating discharge hydrographs for any Average Return Interval (ARI) event. It is required to validate the parameters in rainfall-runoff models against major known storms that exceed at least the 10% annual chance events for single-event analysis if the data are available. The data to validate the model should include the following:

- Peak flood discharges developed at gauging stations, computed by indirect methods, or flood discharge hydrographs (available from responsible agencies like hydro-met agency or similar)
- Rainfall distribution, reported at minimum with hourly intervals, at rain gauges within or near the watershed being under consideration
- Total rainfall values at rain gauges or isohyetal map for a particular storm, indicating the duration of the storm, and
- Rainfall and soil moisture conditions before the storm for single-event analysis

Observed high-water marks may be of value when validating a hydrologic model. In gauged basins, where high water marks from major flood events are available, the rainfall-runoff model should be validated with the significant high-water marks. If no high water marks from major events exist, and regression equations are determined not to be applicable, a detailed explanation of the rainfall-runoff model should be provided and the model should be reviewed in detail to determine flood discharge reasonableness.

The plausibility of the rainfall-runoff model should be checked by executing a number of simulations of past-observed events with the model, to find the range of uncertainty in the results and physically based reasons for the differences between the simulated and observed flood discharges of flood flow-frequency analysis. After this, the impact of these deviations and uncertainties needs to be explored with respect to the exploitation results.

Regardless of whether models have been validated with historical events, further runs may be required to produce flood flows from several selected design storms that are comparable to the flood flows from the flow-frequency analysis, if records are available. If reasonable matches cannot be reached by maintaining models' parameters within acceptable ranges (physical significance), then the model methodology and its application should be reviewed.

Step 1.5: Discharge simulation for design storm events

Following the validation step, the model is ready for exploitation and flood discharge simulation for the design rainfall of selected ARI. Rainfall Intensity-Duration-Frequency functions or curves are mostly suitable information for estimating design rainfall for an ARI.

Where models are validated with historical events and are applied properly after analysis of the morphological changes of the river including new structures, and if the modelled flood flows and frequency flood flows do not agree, the design rainfall volume and distribution may require adjustment. The design rainfall distribution should be selected from traditional distributions prepared by relevant agency.

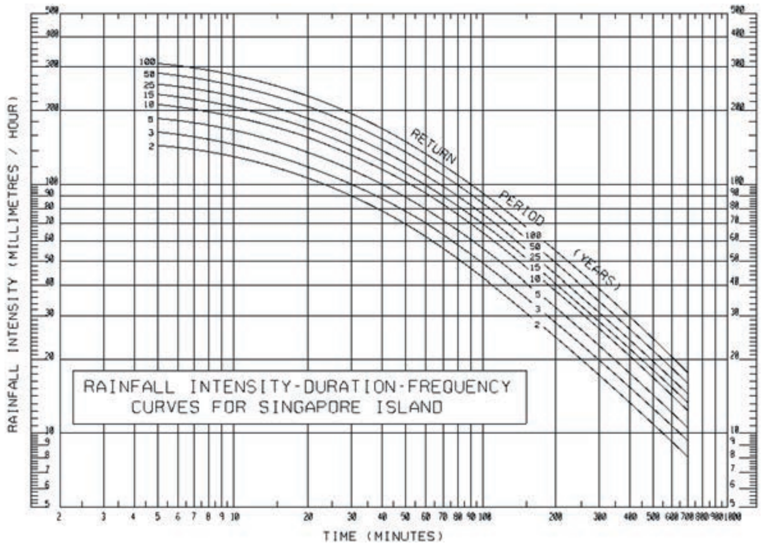


Figure 39 — Rainfall intensity-duration-frequency curves (PUB, Singapore's National Water Agency)

After the simulation, the simulated flood discharge data for any ARI event will be available for various applications and uses including the hydraulic modelling of flood prone areas for which these outputs will serve as the boundary conditions. It is recommended to simulate flood discharge for a frequent, rare and very rare event.

The model can be also utilized to simulate flood discharge under different development and environmental changes scenarios. However, it has to be ensured through sensitivity analysis that the calibration parameters are not sensitive to the scenario for development or change. Otherwise, the model parameters have to be adjusted to best represent the proposed development or change scenario in the watershed.

2.3 Flood Modelling

Hydrodynamic fluvial flow models are widely applied in the engineering business with the availability of high performance personal computers. One- and two-dimensional flow models as outlined are in the meantime standard applications in the hydraulic design of rivers and flood mitigation measures. For reasons of quality and efficiency the determination of flood prone areas by hydraulic models should follow strictly the following sequence of actions:

- Step 2.1: Delineation of study area;
- Step 2.2: Selection of modelling approach for fluvial flow simulation;
- Step 2.3: Data collection and collation for model set-up;
- Step 2.4: Model calibration and validation;
- Step 2.5: Flow simulation for the flood events;
- Step 2.6: Determination of the inundated area.

Step 2.1: Delineation of study area

The first step in setting up a hydraulic model of the river is to define the upstream and downstream end of the model area. Best locations for these model boundaries are river locations where the water stage and discharge is recorded and reliable stage-discharge relationships exist. In this case direct boundary conditions can be defined which minimize the error of the model at these boundaries.

If no gauging station exists close to the study area, the model area needs to extend considerably beyond the study area because the boundary values have to be determined on the assumption of uniform steady flow. Under these conditions a single corresponding water depth exists for a given discharge. The impact of wrong assumptions of the boundary values on the computational result varies considerably in dependence on the topographic gradient, roughness condition and geometry of the river bed. Therefore, the extent of this erroneous region cannot easily be determined prior to the calculation. In fact the initial assessment has to be confirmed through a sensitivity study in which the boundary values are varied systematically showing the impact of the boundaries on the flow domain. The longitudinal boundaries which restrict the flood model sidewards have to be beyond the expected inundation line which can be derived either from historic flood events, the extent of the river valley or the preliminary flood maps. They need to be confirmed with the first results of the model and adjusted accordingly.

No hydro-dynamic flood modelling should be set up without field observation. The information from maps, photos and graphs cannot provide sufficient understanding of the local roughness and flow conditions. A walk along the river will give a good impression on the morphodynamics, hydraulic conditions (e.g. occurrence of hydraulic jumps, backwater zones, accelerated and branching flow sections). In preparation of the field survey this first preview of the flow domain will help to decide about location and density of cross-sections and terrain profiles. Hydraulic structures such as weirs, dams, hydropower plants and other structures should be registered and their impact on the flow assessed. Additionally, bridges and culverts need to be detected and evaluated. A field protocol should be established, integrating notes, maps with marked locations, sketches and photos.

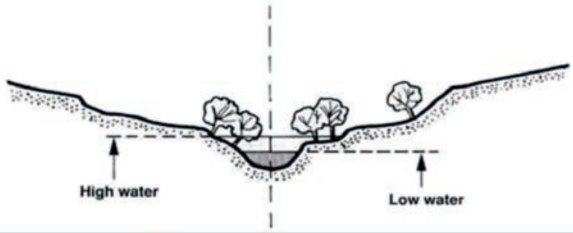
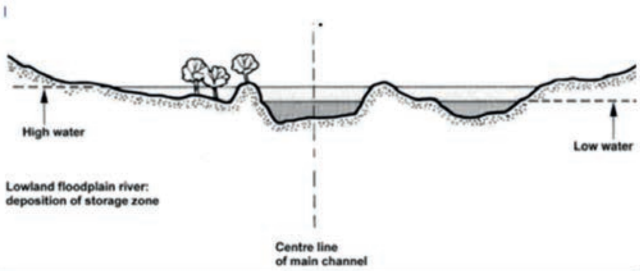
Step 2.2: Selection of modelling approach for fluvial flow simulation

With the information collected in the field a distinct decision on the right modelling approach can be accomplished. The main questions to be answered are:

- the dimension of the model: 1-dimensional, 2-dimensional;
- the coverage of the flood dynamics: steady or unsteady flow regime;
- the appropriate flow resistance approach (especially for shear stress due to bed roughness, vegetation, composite cross-section or roughness); and
- the handling of hydraulic jumps and hydraulic structures (bridges, weirs, culverts).

It is recommended to determine the right modelling tool by making use of **Table 4**. But the selection of the modelling tools is not only determined by the physical criteria. In the same way the availability and quality of the required data and the desired accuracy of the hydraulic results are influencing the choices. In urban environment the flood risk is high and thus calls for precise flood mapping. Consequently, in urban areas the requirements of accuracy are higher than in rural areas. But also the interest of stakeholders to develop their urban land calls for accurate flood maps to avoid controversial discussions and disbelieve in the flood maps. It is recommended to determine the water depth with an error of less than 10 cm and the flow velocity with an error of less than 20 cm/s along urban rivers which can be accomplished for a good data situation and the modelling tools applied according to **Table 4**. In rural areas, or under data-scarce situations, the corresponding error should be of the order of 25 cm and 50 cm/s, respectively.

Table 4 — Complexity of flow in dependence on morphological and hydraulic structure

Structural property	Flow phenomena	Dimension of flow	Modelling approach
Cross-section			
Compact			
	Plane flow, 2^{nd} order flow negligible	1d	Eq. 2
Composite			
	Strong lateral velocity gradient, momentum exchange (interaction)	2d or 1d, if divided in flood-plain and river	Interface regarded as imaginary wall and included in the wetted perimeter
Longitudinal profile			
Straight and steep gradient	Uniform, supercritical flow	1d	Eq. 2 solved for each cross-section from upstream to downstream
Cascade (pool-riffle-riverbed)	Non-uniform flow, super-critical and subcritical flow alternating	3d; 1d, if regarded as sequence of weir – and plane flow	Eq. 3 , combined with weir flow
Gradual extension or narrowing	Non-uniform flow	2d or 1d, if contraction/ extension loss included	Eq. 1 or Eq. 2 with contraction/extension model
Sudden extension/ contraction	Non-uniform, hydraulic jump, flow separation, re-circulating flow	2d/3d; 1d, if discontinuity regarded as local loss	Eq. 1 or Eq. 2 with contraction/extension model
Lateral inflow or outflow	Unidirectional, transversal momentum flow, flow separation with re-circulation	2d or 1d, if transversal momentum flow considered	Eq. 1 or Eq. 2 with local loss approach
Meandering	Spiral secondary current	3d, 2d or 1d if secondary current considered	Eq. 1, secondary current included in dispersion terms, Eq. 2 secondary current considered as local loss/additional friction
Braiding or island	Transversal momentum and flow separation wit large eddies	2d or 1d, if flow separation considered	Eq. 1 or Eq. 2, if flow separation considered as local loss

Structural property	Flow phenomena	Dimension of flow	Modelling approach
Perimeter			
Fine to coarse bed material	Boundary layer flow	Bed roughness	1d-model: Eq. 6, 2d-model; Eq. 7 and Colebrook/White resistance law
Very coarse bed material	Boundary layer flow mixed with form drag	Extreme bed roughness	Special resistance model (e.g. Aguirre-Pe & Fuentes, 1990)
Submerged vegetation	Bed shear stress and vegetation deflection	Bed roughness with biomechanical behaviour of vegetation	Special resistance model (e.g. Kouwen)
Non-submerged vegetation	Form drag	Form resistance model	Eq. 8
Composite roughness	Bidirectional momentum exchange, turbulent shear stress at interface	Dividing cross-section in flood-plain/main channel and introducing imaginary wall in the wetted perimeter	Eq. 9 and 10
Bed forms	Bed shear stress, bed load, drag flow at riffles, dunes	Bed roughness with special consideration of form resistance	Eq. 4/6 and 5/7 with friction factor considering bed forms
Local scour at bank or bed	Drag flow	Form resistance	Local loss approach
Bridges/culverts			
Constriction by abutments and piles	Backwater effect, flow acceleration within structure with the chance of hydraulic jump	Form resistance	Local loss approach (e.g. Yarnell)
Sudden extension/contraction	Non-uniform flow, hydraulic jump, flow separation, re-circulating flow	Form resistance regarded as local loss	Contraction/extension model
Bridge construction	Pressure flow, weir flow, hydraulic jump	3d, 1d, if separated into two flow components (weir and pressure flow)	Pressure flow by Bernoulli with local losses for flow separation, weir flow with Poleni-formula

Step 2.3: Data collection and collation for model instantiation

The availability and quality of data are most important for a reliable determination of the flood prone areas using hydraulic models. Input data of these models are:

- Geographic data such as:
  - Topography based on DTM of the ground surface and Aerial images;
  - Land use distribution including wooden vegetation and biotopes; and
  - Bathymetry of river bed.
- Hydrological/hydraulic data such as:
  - Stage discharge relationship at the downstream end of the river section under consideration;

- Historic flood data: water surface elevation, flow velocities and delineation line of inundation;
- Full hydrograph of water stage and/or discharge, including peak discharge, at upstream and downstream end of the river section
- Roughness parameters, turbulence parameters and local form and drag resistance

The topography is generally available through maps that include the terrain/relief and the spatial distribution of objects on the surface, as water bodies, transportation lines, developed areas, political and administrative borders. In general the scale should not be less than 1:25,000. But in case the flood maps have to show the inundation and flood risk on a property level than maps in a scale of 1:5,000 or 1:10,000 are necessary as they come in general with the property lines **(Figure 41)**.

Step 2.4: Model validation

Despite great progress in the simulation capabilities of today's hydraulic software systems they are still reducing the complexity of real systems and thus only approximate reality. The more simplification, the more is the chance that the empirical parameters are not physically based but need to compensate for deficiencies in the modelling of important flow processes. Experience and good understanding related to flow processes in fluvial rivers are needed to accomplish a physically based calibration of the empirical parameter. The less the spatial distribution of the surface roughness and vegetation is defined in the data model the harder it will be to accomplish the target of physically sound calibration. The consequence can be that the model is only valid for the flow situation and water depth which is comparable with the calibration event.

In the concept of Manning's roughness, the roughness parameter is not constant. Manning's *n* is varying considerably over the water depth especially for river banks and flood plains covered with wooden vegetation and makrophytes (Pasche, 2007). Therefore, it is necessary to calibrate these parameters at least at one small and one extreme flood event. Also for turbulence models with constant eddy viscosity, the viscosity parameter varies over the water depth considerably which can be only determined through calibration at normal flow and flood flow.

A good calibration result is given if the water depths of the observed flood events are reproduced with an average error of less than +/- 5 cm with a maximum error of 10 cm, assuming reliable observations. This will not be feasible with 1-dimensional models if fluvial floods produce strong 2- and 3-dimensional flow situations. Deviations of more than 20-30 cm are possible in river bends with extreme lateral gradients of the water level. Two-dimensional flow models can reproduce these flow situations with errors of less than 10 cm but need a refined turbulence model or calibration of the dispersion terms. Major errors are possible with 2-dimensional models at bridges or weirs with the occurrence of pressure flow or a hydraulic jump. In these cases it is necessary to give up the shallow-water-equation and use empirical relationships based on the Poleni equation to describe the relationship between the upstream and downstream water level at the hydraulic structure and the discharge over the structure.

Table 5 — Testing procedure for hydraulic models

Phases of Model Testing	Flow parameter	Flow events	Criteria to meet
Phase I: Calibration	Local Water level Mean water level along thalweg Local depth-averaged velocity	**Normal flow:** mean flow, bankfull flow **Flood flow:** small event (1-year, 10-year flood) extreme event (50-year, 100 year flood)	**Water level:** Mean: +/- 5 cm Maximum: +/- 10 cm **Flow velocity:** Mean: +/- 10 cm/s Maximum: +/- 20 cm/s
Phase II: Validation	Local Water level Mean water level along thalweg	**Normal flow:** 1 event, different from calibration **Flood flow:** 1 event, different from calibration	**In urban areas:** Water level: max +/- 10 cm Flow velocity: mean +/- 20 cm/s **In rural areas:** Water level: mean +/- 20 cm
Phase III: Reassessment	*In case of no validation, reassessment of input data and selected model approach*		

Before applying a calibrated model it is recommended to validate the empirical parameters at two more observed flow events, preferably one at normal flow and one at flood. The empirical parameters are not changed in these test runs. Then the deviation between the numerical results and observations is an indicator of the reliability of the model and the soundness of the assumed empirical parameters. In the best case the deviation are within the range of the calibration. But the validation only needs to meet the requirements defined in **Step 2.2**. They are dependent on the damage potential on the flood prone areas and need to be clarified with the stakeholders and water authorities. The criteria given in Table 5 can be used. If the validation targets cannot be fulfilled the model first needs recalibration at all calibration events before the validation process is repeated. If this does not converge to the defined validation criteria the choice of the modelling approach and the quality of the input data have to be reassessed and improved.

Step 2.5: Flow simulation for the design flood events

Following the validation step, the model is ready for exploitation and the simulation of the flow processes for the design flood events (as determined through the procedure described in **Section 4.2.3**). The results of the flow simulation are the water level and the flow velocities within the river section covered by the model. In case of a 1-dimensional hydraulic model, water level and flow velocities are given as average values within a cross section. In models where flood plain and main channel are calculated separately in different stream tubes the flow velocity is given as an average value of each stream tube. The 1-dimensional models also give the length of the wetted perimeter and the delineation points of the water surface. Thus within a cross-section the extent of inundation can be already recognized.

For 2-dimensional flow models the results are the spatial distribution of the water depth and the depth-averaged velocity components in the horizontal plane. From these data the delineation line of the inundation area can be derived **(Figure 40)** as long as the model covers the whole flood prone area. But often the 2-dimensional flow model is restricted to those flood-prone areas which are only contributing to the conveyance leaving unconsidered flooded areas which contribute only by storage of flood water (retention).

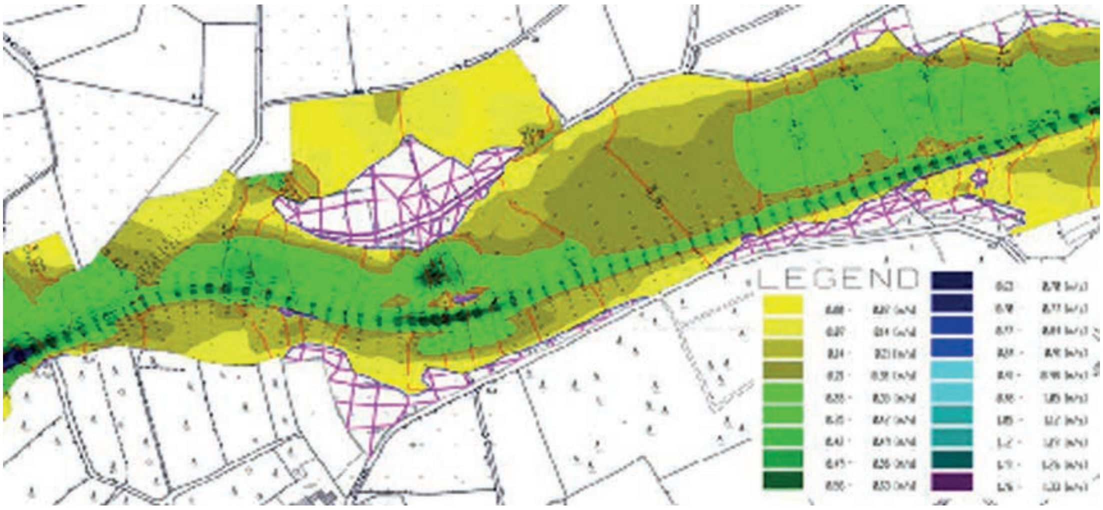


Figure 40 — Examples of a visualized result from a 2-dimensional fluvial flood simulation

Step 2.6: Determination of the outline of inundated area

The final delineation of the inundation area needs the combined use of the DTM of the ground surface and the calculated water levels from **Step 2.5**. Both these data have to be transformed into a grid of the ground surface and the water table, respectively. While this task is easily accomplished for the DTM of the ground surface by applying standard GIS-tools, the derivation of a grid for the water table needs additional processing of the calculation result. For a two-dimensional model the numerical grid can be used as basis for the grid of the water table. It has to be extended if the numerical grid does not cover the whole inundated flood plain but only the conveyance region. The grid of the DTM has to be merged with the grid of the water table for these uncovered flood plain regions. The water surface elevation at each node of the merged grid has to be derived from the simulation results of the nodes lying closest to the merged grid, thereby assuming that within the merged grid no transverse gradient of the water surface occurs.

More complex is the derivation of a grid-based water table from the 1-dimensional model. First it has to be assured that in each cross-section of the hydraulic model delineation points on both sides of the river bed or flood-plain are given. Otherwise the cross-sections have to be extended by interpolation with the DTM of the ground surface. The delineation points of all cross-sections are connected to a TIN (triangular irregular network) in which the lines of the cross-sections are regarded as break-lines. Again this TIN has to be transferred into a grid with the same resolution and the locations of the grid nodes being identical with the ones of the ground surface.

These two grids of the water surface and ground surface are the basis for visualizing the inundated area, water depth and water surface elevation which can be accomplished with standard GIS-functionality. It is recommended to resolve the grid by minimum cell size of 2m.

In this case, the discontinuous delineation lines are only recognized as continuous lines in a map with the scale of 1:5,000.

The irregularity of the terrain can lead to several geometrical artefacts, which need manual correction. In flat topographies water bodies are determined outside the inundation area and need to be excluded. Another artefact is a ragged inundation area where a clear delineation line is hard to determine. In this case the delineation of the inundated area has to be smoothened. A third problem is created by small islands within the inundation area. They might be also an artefact or too small for being excluded from the inundation area. Criteria have to be defined for disregarding these islands. An example of post-processing of the inundation area and the definition of the final delineation line is given in **Figure 41**.

A delineation line shows the inundated area for one specific flood event. This process of delineation has to be repeated for all flood events selected for the flood hazard and flood risk analysis. The inundation area of at least three flood events is needed in a flood risk assessment.

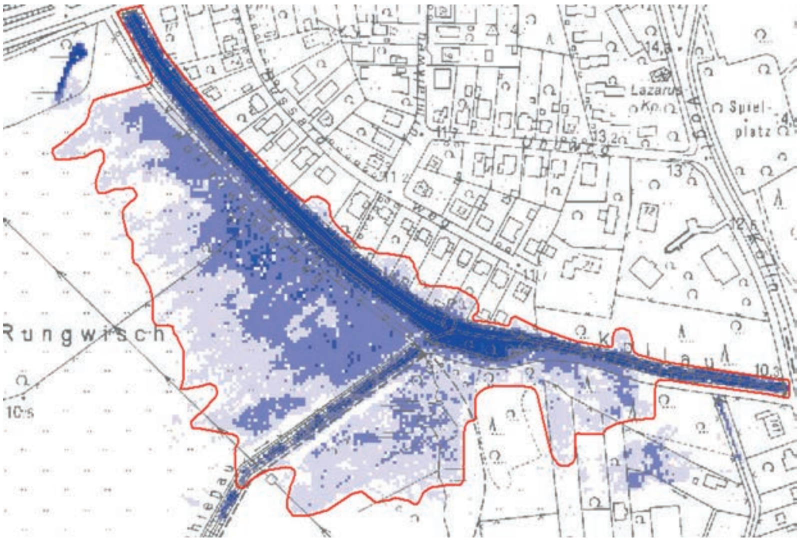


Figure 41 — Inundation area, excluded from geometric artefact through a smoothed delineation line

The model can also be used to study the impact of different drivers such as climate change, urban development and environmental changes in the river (scenario analysis). However, it has to be ensured through sensitivity analysis the calibration parameters are not sensitive to the scenario development or change. Otherwise, the model parameters have to be adjusted.

For more information, please contact:

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