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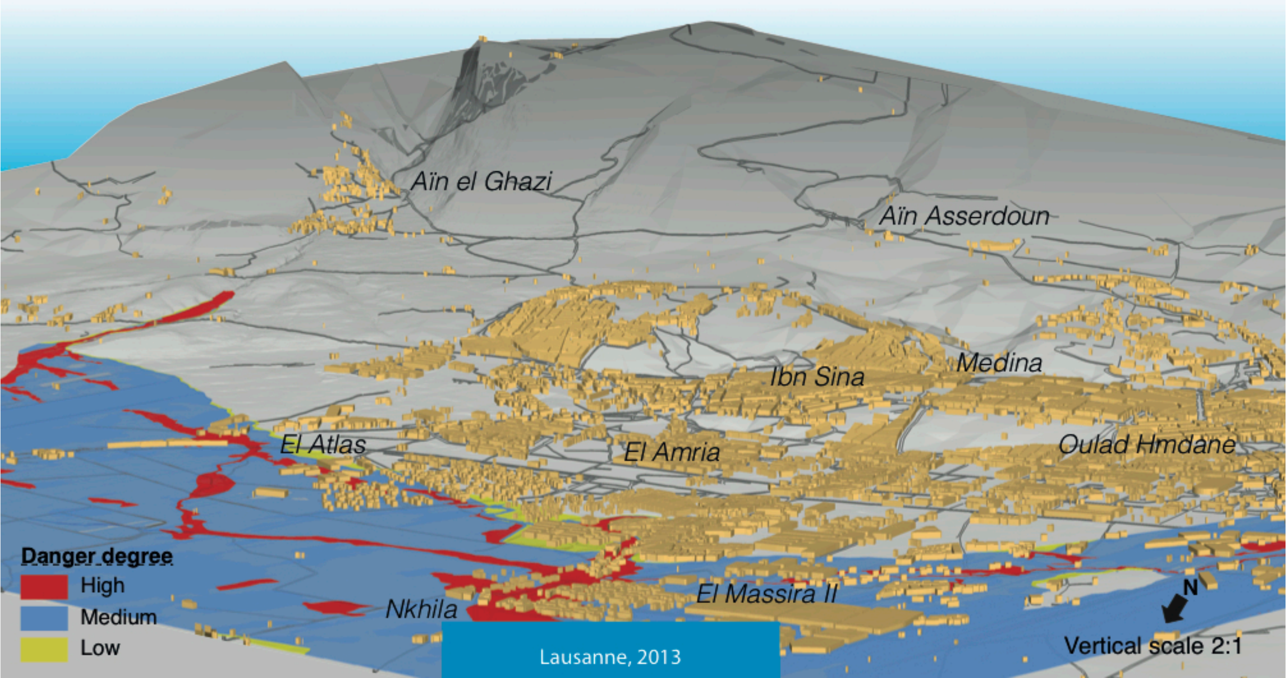
Gabriela Werren



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Maps as risk mitigation tools. Adaptation of the Swiss hazard assessment and mapping methodology to a Moroccan site: Beni Mellal

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BENI MELLAL**

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Content

Abstract

Severe rainfall events are thought to be occurring more frequently in semi-arid areas. In Morocco, flood hazard has become an important topic, notably as rapid economic development and high urbanization rates have increased the exposure of people and assets in hazard-prone areas. The Swiss Agency for Development and Cooperation (SADC) is active in natural hazard mitigation in Morocco. As hazard mapping for urban planning is thought to be a sound tool for vulnerability reduction, the SADC has financed a project aimed at adapting the Swiss approach for hazard assessment and mapping to the case of Morocco.

In a knowledge transfer context, the Swiss method was adapted to the semi-arid environment, the specific piedmont morphology and to socio-economic constraints particular to the study site. Following the Swiss guidelines, a hydro-geomorphological map was established, containing all geomorphic elements related to known past floods. Next, rainfall / runoff modelling for reference events and hydraulic routing of the obtained hydrographs were carried out in order to assess hazard quantitatively. Field-collected discharge estimations and flood extent for known floods were used to verify the model results. Flood hazard intensity and probability maps were obtained. Finally, an indicative danger map as defined within the Swiss hazard assessment terminology was calculated using the Swiss hazard matrix that convolves flood intensity with its recurrence probability in order to assign flood danger degrees to the concerned territory.

Danger maps become effective, as risk mitigation tools, when implemented in urban planning. We focus on how local authorities are involved in the risk management process and how knowledge about risk impacts the management. An institutional vulnerability "map" was established based on individual interviews held with the main institutional actors in flood management. Results show that flood hazard management is defined by uneven actions and relationships, it is based on top-down decision-making patterns, and focus is maintained on active mitigation measures. The institutional actors embody sectorial, often disconnected risk knowledge pools, whose relationships are dictated by the institutional hierarchy. Results show that innovation in the risk management process emerges when actors collaborate despite the established hierarchy or when they open to outer knowledge pools (e.g. the academia). Several methodological and institutional recommendations were addressed to risk management stakeholders in view of potential map implementation to planning.

Hazard assessment and mapping is essential to an integrated risk management approach: more than a mitigation tool, danger maps represent tools that allow communicating on hazards and establishing a risk culture.

Résumé

Dans le contexte climatique actuel, les régions méditerranéennes connaissent une intensification des phénomènes hydrométéorologiques extrêmes. Au Maroc, le risque lié aux inondations est devenu problématique, les communautés étant vulnérables aux événements extrêmes. En effet, le développement économique et urbain rapide et mal maîtrisé augmente l'exposition aux phénomènes extrêmes. La Direction du Développement et de la Coopération suisse (DDC) s'implique activement dans la réduction des risques naturels au Maroc. La cartographie des dangers et son intégration dans l'aménagement du territoire représentent une méthode efficace afin de réduire la vulnérabilité spatiale. Ainsi, la DDC a mandaté ce projet d'adaptation de la méthode suisse de cartographie des dangers à un cas d'étude marocain (la ville de Beni Mellal, région de Tadla-Azilal, Maroc).

La méthode suisse a été adaptée aux contraintes spécifiques du terrain (environnement semi-aride, morphologie de piémont) et au contexte de transfert de connaissances (caractéristiques socio-économiques et pratiques). Une carte des phénomènes d'inondations a été produite. Elle contient les témoins morphologiques et les éléments anthropiques pertinents pour le développement et l'aggravation des inondations. La modélisation de la relation pluie-débit pour des événements de référence, et le routage des hydrogrammes de crue ainsi obtenus ont permis d'estimer quantitativement l'aléa inondation. Des données obtenues sur le terrain (estimations de débit, extension de crues connues) ont permis de vérifier les résultats des modèles. Des cartes d'intensité et de probabilité ont été obtenues. Enfin, une carte indicative du danger d'inondation a été produite sur la base de la matrice suisse du danger qui croise l'intensité et la probabilité d'occurrence d'un événement pour obtenir des degrés de danger assignables au territoire étudié.

En vue de l'implémentation des cartes de danger dans les documents de l'aménagement du territoire, nous nous intéressons au fonctionnement actuel de la gestion institutionnelle du risque à Beni Mellal, en étudiant le degré d'intégration de la gestion et la manière dont les connaissances sur les risques influencent le processus de gestion. L'analyse montre que la gestion est marquée par une logique de gestion hiérarchique et la priorité des mesures de protection par rapport aux mesures passives d'aménagement du territoire. Les connaissances sur le risque restent sectorielles, souvent déconnectées. L'innovation dans le domaine de la gestion du risque résulte de collaborations horizontales entre les acteurs ou avec des sources de connaissances externes (par exemple les universités). Des recommandations méthodologiques et institutionnelles issues de cette étude ont été adressées aux gestionnaires en vue de l'implémentation des cartes de danger.

Plus que des outils de réduction du risque, les cartes de danger aident à transmettre des connaissances vers le public et contribuent ainsi à établir une culture du risque.

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Finally I need to think to my beloved ones, my family, my sister Cerasela, who is my closer family in Switzerland, and last but not least, to Benoit, for all the times he supported me, understood me, and took care of me.

Thank you all.

Glossary

Bour – non-irrigated culture, dependent on precipitation amounts.

Châabat – torrential watercourse

Dir – High Atlas piedmont

Douar – village

Matorral – typical Mediterranean secondary vegetation cover

Medina – Muslim old town

Oued – river, stream

Seguia – traditional irrigation channel

Abbreviations

ABHOER – Agence du bassin hydraulique de l'Oum-er-Rhbia (Morocco)

CAPRA - Central American Probabilistic Risk Assessment

ESRI – Environmental systems research institute

FAO – Food and agriculture organization

FEMA – Federal emergency management agency (USA)

HEC-HMS – Hydrologic engineering center – Hydrologic modelling system

HEC-RAS – Hydrologic engineering center – River analysis system

HFA – Hyogo framework for action

NRC – National research council (USA)

GFDRR – Global facility for disaster reduction and recovery

IPCC – Inter-governmental panel on climate change

LAS – League of Arab states

MATUHE – Ministère de l'aménagement du territoire, de l'urbanisme, de l'habitat et de l'environnement (Morocco)

MELP – Ministry of environmental land protection (Italy)

NRCS – National resources conservation service (USA)

OFEG – Office fédéral des eaux et de la géologie (Switzerland)

OFEFP – Office fédéral de l'environnement, des forêts et du paysage (Switzerland)

OFF – Office fédéral des forêts (Switzerland)

OFPP - Office fédéral de la protection de la population (Switzerland)

OFEV – Office fédéral de l'environnement (Switzerland)

SCS-CN – Soil conservation service – Curve number methodology

SDC – Swiss agency for development and cooperation

SMS – Surface-water modelling solution

UNDESA - United Nations department of economic and social affairs,

UNDP - United Nations development program

UNISDR - United Nations international strategy for disaster risk reduction

USACE - U.S. Army corps of engineers (USA)

1. Introduction

Intense natural phenomena cause substantial human and material losses every year (UNISDR 2011, Munich RE 2012). Some of these phenomena (floods, droughts, cyclones) are thought to have increased in intensity during the last decades, this tendency being often perceived as accountable to climate change (IPCC 2007, Giorgi & Lionello 2008, IPCC 2012). Yet, the actual human impact on the natural environment is not fully explained today (Messerli et al. 2000, Wenger 2006) however this impact is expected to increase during the next decades (Messerli et al. 2000). One must consider therefore the human part of what we call "natural" disasters. Indeed, the growing world population becomes steadily urbanized (50.5% in 2010) (UNDESA 2011) often in uncontrolled sprawl over hazard-prone areas like floodplains or unstable slopes. Rapid urbanization results in many cases in environmental problems likely to emphasize hazardous natural phenomena behaviour (e.g. deforestation, changes in soil permeability, etc.). Flood-related hazards represent in this context an increasing concern.

1.1. Flood hazards: an introduction

1.1.1. Floods: common hazards but emerging risks

When intense natural phenomena interact with and threaten humans and their activities they become **natural hazards** (Tobin & Montz 1997, Alcántara-Ayala 2002). Floods are thought to represent the **most common natural hazard** (Smith & Petley 2009). The United Nations International Strategy for disaster reduction UNISDR (2009) defines hydrometeorological hazard as a "process or phenomenon of atmospheric, hydrological or oceanographic nature that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage" (UNISDR 2009)

When addressing the potential losses related to one hazardous event or in other terms the vulnerability related to one hazardous event, the risk definition appears as "the combination of the probability of an event and its negative consequences" (UNISDR 2009), that was classically written as the risk equation (e.g. in Dauphiné 2001, Wisner et al. 2004 among others):

$$R = H * V \tag{1.1}$$

where R= risk, H= hazard, and V=vulnerability. Hazard studies detailed in Chapter 2 have proven that the risk equation is more complex and difficult to solve.

In developing countries, floods still cause important human losses while developed countries face substantial material damage that is yet poorly insured (Wisner et al. 2009, MunichRE 2010). Increasing flood-related disasters are perceived as a direct consequence of climate change. Nonetheless, humans define risk. Indeed, people's exposure to flood hazard has increased since 1970 more rapidly than the world population itself (114% versus 84%) (UNISDR 2011). This situation is prevailing in low-income countries that see their development hindered by repeated human and material losses related to floods (SDC 2008). Natural hazards may deeply impact **countries' development** revealing its limits. Indeed, there is a direct relationship between natural disasters and poverty, as damages related to the latter represent important obstacles for social and economic development in low-income countries (Wisner et al. 2004).

Flood hazards increase in **semi-arid regions**. The climate change trend characterized by growing aridity backed by more extreme hydro-meteorological events (IPCC 2012) partly explains this fact. Nevertheless, people's exposure to floods has been amplified by 250% since 1970 in North Africa and the Middle East (UNISDR 2011), that is, the human factor must be considered when identifying hazard in this hydro-climatic region. Floods in semi-arid regions often result from convective storms along the outskirts of mountainous regions (Hugonie 2004, Smith & Petley 2009), triggering flash floods with an important damage potential due to their fast-propagating character, high water velocities and high sediment transport capacity (Vinet 2008, Borga et al. 2010). The affected regions are often densely urbanized intra-mountainous valley bottoms or mountain to plain interface areas (piedmonts, alluvial fans and aprons) (Hugonie 2004).

Morocco provides an outstanding example of the relatively recent flood hazard issue affecting developing countries in semi-arid regions (Reynard et al. 2013). Indeed, important population growth and rural exodus towards the outskirts of the mountainous areas have increased exposure to hydrometeorological hazards. Increased rainfall amounts over the last decade resulted in repeated flood-related disasters that also drew attention to the flash flood problem that has affected mountainous regions and their outskirts (UNDP 2006, Saïdi et al. 2010). This situation compels the Moroccan authorities to consider flood hazard management as an integrative panel of the country's water management policies (UNDP 2006).

1.1.2. Risk mitigation aimed at vulnerability reduction

As stated above, floods represent common hazards. Historically, communities have struggled to mitigate flood consequences by acting on the hazard source, i.e. rivers and the river catchments, using an engineering approach to hazard (see Box 1-1). Nevertheless, statistics show that people's exposure to hazard increases constantly due to the fast pace of urbanization making more people and territories vulnerable to potential damages of floods (Hewitt 2013). In most cases, as stated by the structuralist school of thought (see Box 1-1), urban developments rarely follow deliberate choices. Instead, uncontrolled urbanization in hazard-prone areas is often a consequence of unbalanced development (Tobin & Montz 1997, Smith & Petley 2009). One can hence conclude that people's vulnerability to flood hazards represents the main term of the risk equation, at least in densely populated urban areas. Therefore, to mitigate risk, one must address vulnerability and reduce it.

"Natural" disasters represent complex systems (see Box 1-1) whose components mutually control each other. The rising awareness of this complexity lead to the emergence of an **integrated risk management approach** (Loat & Zimmermann 2004, Kienholz 2005) that focusses on all mitigation measures deployed before and after an event's occurrence. The conceptual components of this approach are described in section 2.1.

Flood hazard approaches: a short story

Natural hazard and risk concepts stem in the probability and cause-effect laws that replaced the Christian idea that natural disasters were of divine origin and thus inevitable (Covello & Mumpower 1985, Wackermann 2004). Yet, since the Middle Age and until the 20th century, river "domestication" via important hydraulic works was undertaken with the idea that protection infrastructures should be sufficiently solid to resist major floods. Emphasis was set on hazards as defining elements for risk (Cardona 2003). This **engineering paradigm** (Smith & Petley 2009) continues to mark flood hazard management nowadays.

Around 1950, the **behaviourist paradigm** (White 1973, Burton et al. 1978, Smith & Petley 2009) stated that natural hazards embed a human component related to the communities' deliberate choice to settle in hazard-prone areas like floodplains. Flood hazard mitigation should therefore better include floodplains management via planning along with the necessary engineering protection measures (Smith & Petley 2009). This school of thought first considered vulnerability as a risk factor (Cardona 2003)

In the early 1970s, studies on natural disasters occurring in developing countries proved that communities' choice of settling in hazard-prone areas was rarely deliberate. Moreover, studies in Latin America demonstrated that vulnerability is socially constructed (Wilches-Chaux 1989, Lavell 1997, Maskrey 1994, Cardona 2003) The **structuralist paradigm** emphasised people's vulnerability to hazard stemming in global or regional, contextual or dynamic causes (Wisner et al. 2004, Birkmann 2006). One important contribution was to theorize hazard, risk, vulnerability or resilience as conceptual tools in order to better achieve risk management (Cardona 2003).

A **complexity paradigm** (Smith & Petley 2009) addresses natural hazards in the light of people's relationship to their environment. This theory stems in the statement that "natural" disasters are in majority human-made and that human influence on the environment is poorly explained today (Messerli et al. 2000). Natural disasters are regarded as systems that must be explained by addressing the complex interactions occurring between their components. Despite complexity, the result of these interactions can be predicted, as mutual control establishes between the system's components (Smith & Petley 2009).

Box 1-1. Theoretical approaches to natural hazards, a short story.

At the international level, the integrated risk management approach is materialized in a global resolution, i.e. the Hyogo Framework for Action (HFA) that sets the priorities nations should achieve in reducing natural disaster risks for the decade 2005-2015. HFA represents the outcome of the 2005 World Conference on Disaster Reduction that took place in Hyogo, Kobe, Japan (UNISDR 2007, see Appendix 1 for a summary of the HFA priorities for action). Switzerland was actively involved in shaping the HFA (SDC 2011). This text highlights the need for an integrated risk management strategy at the national and local level with a focus on proactive risk mitigation measures.

The integrated risk management approach accounts for the importance of vulnerability reduction measures in mitigating risk, before, during and in the aftermath of a hazardous event. Among vulnerability reducing strategies, **hazard-aware urban planning** can sustainably diminish communities' spatial exposure to hazards. The basis for such planning approaches consists of spatially assessing hazard and vulnerability via **hazard** or **risk maps**. These cartographic documents represent the scientific basis necessary to orient urban planning in a risk mitigation approach. They identify the spatial imprint of potential natural hazards, thus defining the territories' aptitude for specific uses (Loat & Petrascheck 1997). Adapting land use to the existing natural dynamics can, therefore, substantially reduce communities' vulnerability to hazards.

1.1.3. SDC strategy in Morocco. Project context

The Swiss Agency for Development and Cooperation (SDC) is actively involved in disaster risk reduction in Morocco (SDC 2011). In agreement with the integrated risk management approach, SDC developed several projects aimed at communities' vulnerability reduction, be it by enhancing people's coping capacity during natural disasters, strengthening the prevision capacity for better pre-event alert or reducing urban communities' spatial exposure to natural hazards via hazard assessment and mapping designed for planning purposes. SDC supports the integrated risk management approach in Morocco (see Box 1-2).

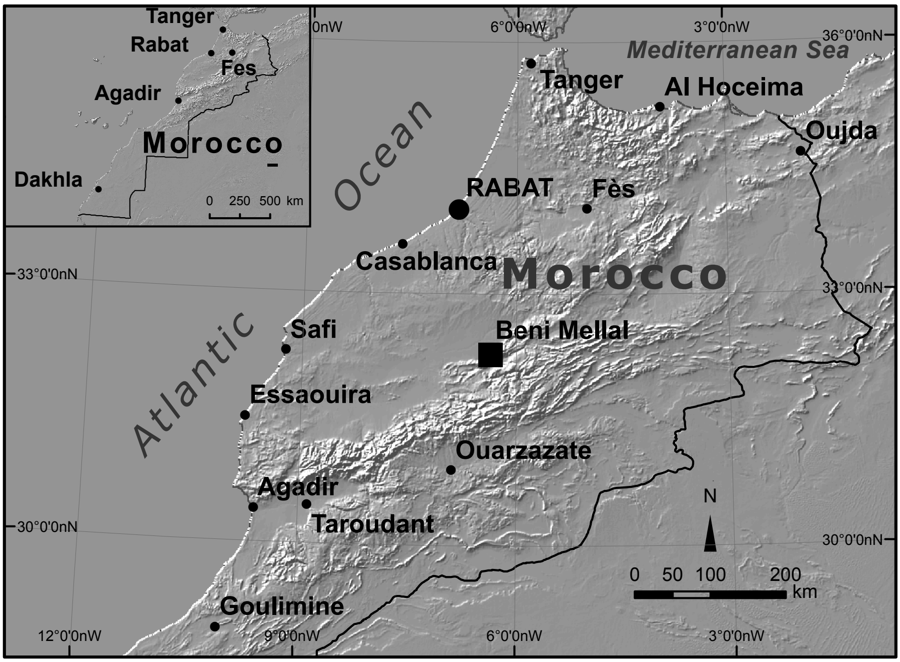


Figure 1.1: Study site localization map: Beni Mellal, Morocco.

In the relatively recent hydro-meteorological context marked by an increased frequency of high intensity rainfall events, Moroccan urban areas situated at the outskirts of the Atlas Mountains are systematically exposed to flooding hazards (BRL, ADI, Aquater

2004). Sensitive to the important risk-mitigating role of hazard-aware planning, SDC gathered experience in adapting the well-established Swiss hazard map methodology in several partner countries (Zimmermann et al. 2005). The present project, "Flood risk management in two Moroccan urban catchments, Fez and Beni Mellal", was developed in Morocco between 2009-2012. By addressing **flood risk mitigation via hazard assessment and mapping for planning purposes** (Reynard et al. 2011a, 2011b, 2012, 2013, Werren 2013), this study aims at adapting the Swiss hazard assessment and mapping method to specific Moroccan contexts. The study was grounded on several mapping field surveys between 2009-2010, methodological research, cartographic design of assessment documents and management-related surveys.

SDC involvement in disaster risk reduction (DRR) in Morocco

DRR issues are part of the economic development and employment priority domain the SDC developed in Morocco (www.dsc.admin.ch). Since 2007, different projects aimed at mitigating people and communities' exposure to natural hazards and their consequences were undertaken.

The volunteer neighbourhood disaster relief workers project (*Secouristes Volontaires de Proximité SVP*) trains locals of several Moroccan historic centres (*medinas*) in emergency rescue techniques specially adapted to these poorly accessible urban perimeters. (Zumstein 2010). This project increases local population resilience to natural disasters (www.dsc.admin.ch).

The flood pre-alert system installed with SDC assistance in the upper catchments of the Fez urban area represents another example of a resilience enhancing project aimed at diminishing local population vulnerability to floods (www.dsc.admin.ch).

The Swiss hazard assessment and mapping method adaptation for flood hazards in Fez and Beni Mellal aims at providing Moroccan authorities with tools for reducing urban areas' physical exposure to floods by assessing hazard and orienting future planning (www.dsc.admin.ch).

Since 2009, an integrated strategy for disaster risk management emerged as a close collaboration between the Moroccan government, SDC and the World Bank. This project replaces the sectorial approaches previously undertaken in DRR in Morocco with a comprehensive vision on disaster risk reduction involving several ministries and aiming at concerning local authorities throughout the country to the DRR effort. This project aims at providing comprehensive risk modelling as a decision tool for sectorial action, campaigning DRR at the local level and advocating risk reduction measures implementation within local planning documents (Poretti 2011).

Box 1-2. SDC disaster risk reduction projects in Morocco.

Two urban catchments were selected for flood hazard assessment and potential hazard map implementation: the Fez agglomeration set at the outskirts of the Moroccan Middle Atlas, and Beni Mellal, capital city of the Tadla-Azilal region, situated on the High Atlas northern piedmont (Figure 1.1). Set at the outlet of several small-scale mountainous catchments, these fast-developing urban areas proved to be particularly vulnerable to flood hazards during the last decade (El Khalki & Benyoucef 2005, El

Khalki et al 2005, Lasri 2011). Flood hazard mapping is expected to offer local authorities the necessary tools for orienting further urban planning in a hazard-aware approach and thus diminishing spatial exposure to flood hazards

This cooperation project not only aims to achieve knowledge transfer of the Swiss experience with hazard mapping, but also aspires to strengthen the academic cooperation between Switzerland and Morocco. Thus, SDC jointly entrusted the adaptation of the Swiss method for flood hazard to the Geo-Environmental Analyses Laboratory (*Laboratoire d'Analyses Géo-Environnementales et Aménagement LAGEA URAC54*) at the Sidi Mohamed Ben Abdellah University in Fez and the Institute of Geography and Sustainability (*Institut de géographie et durabilité IGD*) at the University of Lausanne. Two doctoral theses (Werren 2013b, Lasri 2013), dealing with the adaptation of the Swiss hazard map method in the two urban areas presented above were designed as a direct outcome of this cooperation project.

The two case studies are closely related in their workflow and final results, i.e. flood hazard maps. Within the project common scientific reports that summarize the applied aspects of this research were produced (Reynard et al. 2011b, Reynard et al. 2012). The methodology choice, mapping process, and map design are common to the two study sites; nevertheless specific needs (e.g. alluvial fan morphology in Beni Mellal) required using different methodologies at certain stages of the assessment process. Moreover, due to a lack of time, we addressed vulnerability in a limited manner in Beni Mellal, focussing on institutional risk management; on the other hand, a more complete socio-economical study was undertaken in Fez.

In this work, we present and discuss the adaptation of the Swiss hazard map methodology to the piedmont, flash flood-prone urban catchment of Beni Mellal.

1.2. Problem and motivation

1.2.1. Hazard mapping in the mitigation process: short state of the art

Maps that assess natural hazard or risk have gained recognition as an integrative part of natural hazard mitigation strategies across the world. Indeed, hazard identification and assessment via hazard and risk maps and their implementation at the planning level as a means to "reduce underlying risk factors" are among the priorities set to the international community by the Hyogo Framework for Action (UNISDR 2007).

Why we design flood maps?

The need for hazard identification and assessment via maps and their subsequent production is often related to the occurrence of **catastrophic events** that overwhelm the concerned communities' disaster response and recovery capacity. For example, Hurricane Mitch that struck Central America in 1998 was followed by the emergence of numerous assessment studies at the national and local level (see among others Mastin 2002, Fernandez-Lavado et al. 2007, Furdada et al. 2008) to further be integrated at the regional level (e.g. Central American Probabilistic Risk Assessment *CAPRA* (CAPRA 2012). SDC was actively involved in risk assessment and monitoring in

Honduras and Nicaragua (SDC 2011). Finally, Nicaragua achieved producing high-resolution hazard and risk maps and implemented their findings to development planning (SDC 2011, GFDRR 2012a, b). Likely, recent catastrophic flooding (Morocco 2009, Yemen 2008-2010) and seismic activity (Algeria 2003) as well as severe drought raised attention to disaster risk reduction strategies in the Arab world concretized in the *Arab strategy for disaster risk reduction 2020* that aligns its goals along the Hyogo Framework for Action (LAS 2010).

Switzerland provides another striking example in this sense. Indeed, massive flooding and resulting damages in 1987 compelled Switzerland to change its risk reduction strategy towards hazard-aware planning and to legally make hazard maps compulsory to local communities (Zaugg 2004, Zimmermann et al. 2005, OFEV 2011). In this context, Switzerland developed a comprehensive hazard assessment and mapping methodology that is uniformly regulated and applied throughout the Swiss territory.

Hazard and risk maps may also be produced according to **political**, **contextual** or **economic** triggers. For example, the European Union Flood directive (2007) related to the 2000 Water Framework Directive (Directive 2000/60/EC) represents a **political** constraint to all member states that are expected to identify flood risk zones and to produce flood maps for their national territories by 2015 (EU 2007, Arnaud-Fassetta et al. 2013). Nonetheless, there is an important dissimilarity in the mapping advancement and the utilized methodologies amongst the EU members and within member nations (Van Alphen & Passchier. 2007, De Moël et al. 2009). Indeed, risk and hazard maps are the responsibility of Lands in Germany, cantons in Switzerland, provinces in Spain, and municipalities in France and they are produced using various methodologies. Few European countries have unified their risk assessment methodology and legal framework (e.g. Finland, Luxembourg, Switzerland).

International and regional entities (United Nations, World Bank, League of Arab States), thematic research projects like the SECOA project (Solutions for Environmental Contrasts in Coastal Areas, http://www.projectsecoa.eu), and international cooperation organizations and NGO’s working in the DRR field represent as many potential hazard assessments and maps producers. Their motivation may be political or humanitarian, while the obtained results and emerging methodologies enrich the disaster risk assessment and mitigation field.

Political factors can combine with **economic** ones in hazard mapping for risk mitigation. For example, the United States National Flood Insurance Programme (NFIP) produces Flood Insurance Rate Maps (FIRM) that require landowners of the concerned communities to purchase flood insurance (FEMA, BESR, NRC 2009). The NFIP programme participation is not compulsory; thus, the state uses an encouragement policy towards local communities to integrate NFIP by offering insurance premium subventions and protective mitigation measures. Risk and hazard maps are also produced by the private insurance industry as a basis for damage assessment (Siebert 2000, 2009).

Finally, in developed countries with a long experience with natural hazards, maps have become a part of the **risk resilience culture** and their use is the responsibility of any citizen. For example, in Japan the 2001 Flood Act compels municipalities to design hazard maps to be used by the public in emergency evacuation purposes (Hiroki 2003).

Flood maps typology

There is no established methodology for making risk or hazard maps, be it regarding the inputs or the content of the final map product. For practical reasons, we focus here on maps related to the flood hazard only. Flood mapping generally yields several types of products: flood event inventories, susceptibility maps, hazard maps, risk maps, and hazard maps designed for evacuation purposes. In many cases maps that present inventories of past events are denominated as hazard maps. Risk and hazard maps are decision-making tools that foster hazard aware development if implemented in planning documents. They can be direct (issued of geomorphic mapping) or indirect (issued of models) (Van Westen et al. 1999). Past event inventories represent preliminary documents that inform about past hazardous events and their magnitude. Susceptibility maps aim to identify those areas prone to hazardous events on the basis of sole terrain conditions (Soeters & Van Westen 1996, Guzetti et al. 1999, Santangelo et al. 2011). Evacuation maps are hazard maps that focus on the emergency situations and therefore hazard is assessed as a function of flood intensity and its consequences on people.

Susceptibility maps focus on delimiting areas that have a propensity to be affected by natural hazards (Santangelo et al. 2001). Initially designed for landslide hazards (Soeters & Van Westen 1996, Guzetti et al. 1999), these maps can also be applied to floods. Susceptibility maps do not account for the temporal dynamics of hazards (i.e. the probability of occurrence of an event); therefore, they are thought to be very suitable to alluvial fan environments characterised by high flow uncertainties (Santangelo et al. 2011). They can be direct (issued of geomorphic mapping) or indirect (issued of models) (Van Westen et al. 1999).

Flood hazard maps focus on the natural phenomenon, i.e. flooding, that can be represented by several criteria, according to local specificities of topography or type of flooding:

- Mapped maximum extent of flood inundation for a known, high magnitude event or a modelled reference flood event. Some examples are the U.S. FIRM documents delineating those areas within the 100-year recurrence flood extent (FEMA, BESR, NRC (2009), and several maps produced in France under the PPR (*Plan de Prévention des Risques Naturels*) (Garry et al. 1999).
- Hazard represented by flood intensity in terms of floodwater depth (France, Portugal, the Nederlands) or velocity (Austria) (Van Alphen & Passchier 2007) for given reference events.
- A combination of flood probability represented by maximum flood extent of different reference events and intensity represented by water depth, and / or velocity (Great Britain, Rheinland-Pfalz land in Germany, Switzerland) (Kienholz & Krummenacher 1997, Van Alphen & Passchier 2007).

Danger maps, developed in Switzerland, are hazard maps that contain land use specifications corresponding to assessed degrees of threat to people, animals and infrastructure (Kienholz & Krummenacher 1997, OFEV, OFEG, OFEFP 2005, see Section 2.2.2 for a broader description).

Risk maps are the product of hazard and vulnerability maps and they account for the potential adverse consequences of hazardous events on the affected areas (Directive 2000/60/EC). Some European countries (Italy, Spain) have produced such maps (MELP-Italy 2006, Van Alphen & Passchier. 2007). In developing countries, assessing vulnerability has become the goal of recent disaster risk reduction measures in the line of the Hyogo Framework for action (GFDRR 2012a). The CAPRA project in Central America (CAPRA 2012) is an example of coordinating risk assessment methodology at the regional level. Risk assessment is mainly qualitative as vulnerability is a highly complex and subjective criterion (Wisner et al. 2004, Birkmann 2006). Moreover, quantitative risk assessments of material or optionally immaterial losses due to hazardous events are particularly used by the insurance industry (Siebert 2000, 2009, Berz et al. 2001).

Moroccan flood hazard mitigation today

Flood hazards management is addressed by the Moroccan Water Act (10/1995) that regulates the creation of nine catchment agencies as water management regional authorities. These agencies' attributions encompass the "implementation of measures, gauging, and hydrological and hydro-geological studies for the quantitative and the qualitative planning and water management and **the setting up of the necessary infrastructure for flood prevention and protection[1]**"(Section 20, our translation). Older law texts deal with flood and erosion prevention via protective forests (Act 10/1917, Act 1/1969). The Water Act only stipulates active measures of flood mitigation. Hazard mapping for urban planning is not yet regulated in Morocco.

The 2003 National flood protection plan inventoried and mapped 394 flood prone sites. Risk was assessed qualitatively as human, building, infrastructure, and environmental, economic or agricultural risk (BRL, ADI, Aquater 2004). This study planned to assess risk relative to flood intensities and related vulnerability, however no maps were further produced. Catchment agencies actually produce flood maps that may take the form of mere flood prone sites inventories or actually depict flooded areas for several modelled flood events for further flood protection measures and hydraulic structures calibration (e.g. ADI 2004, ADI, ABHOER 2006). Several agencies publish a "Flood Atlas" on the Internet consisting of flood extents for known reference floods. For example, in the Ourika valley where the 1995 catastrophic flash flood raised awareness about flood hazards across the country (Saïdi et al. 2010). In this case, hazard mapping is used as a tool for early warning and awareness making.

A pilot project mandated by the Al Hoceïma regional authorities plans to design "urbanization aptitude maps" for the region's urban centres as a function of the risk situation assessed for multiple natural hazards: earthquakes, landslides, floods (IMS-RN

[1] « Réaliser toutes les mesures piézométriques et de jaugeages ainsi que les études hydrologiques, hydrogéologiques, de planification et de gestion de l'eau tant au plan quantitatif que qualitatif (…) réaliser les infrastructures nécessaires à la prévention et à la lutte contre les inondations »

2011). The pilot project is presently in a validation phase.

Recent developments at the international and national level tend to shift flood risk management towards a more unitary and planning-oriented strategy. On one hand, the Moroccan involvement in the Arab strategy for disaster risk reduction (LAS 2010) includes the implementation, at least at the political level, of the Hyogo Framework for Action priorities that emphasize planning as a sound tool for vulnerability reduction. On the other hand, a national risk assessment strategy, financed by SDC, the Moroccan government and the World Bank was adopted (SDC 2011). This strategy aims at assessing risks on a probabilistic basis at the national level and mainstream disaster risk reduction at the local level by implementing DRR in the municipal development plans (SDC 2011).

Academic studies of flood hazard mapping remain marginal. We can name the application of a geomorphic method for flood hazard mapping in the Sebou valley (Taous et al. 2010). Several studies issued of the Mohammedia Engineering School in Rabat deal with flood risk protection via structural measures (Kaddaf & Boufous 2010) or perform hazard assessment for further risk mapping (Benjelloun 2009) without actually producing planning-suitable hazard or risk maps.

1.2.2. Motivation

Flood risk mitigation via hazard-aware planning and implicitly flood risk and hazard maps are well developed almost exclusively in **developed countries**. Awareness on the limited effectiveness of purely structural mitigation measures following over 100 years of flood hazard mitigation effort might justify this fact. Protection infrastructure, costly to build and to maintain failed to provide an absolute protection guarantee during extreme events. Thus, an emergent Humans-Environment relationship paradigm reconsiders riverine corridors as a risk mitigation element as floodplains and wetlands absorb excess flows during important flood events (Zaugg 2004). In this context, urban planning and river floodplain partial rehabilitation mitigate flood risk complementarily. Moreover, high-income countries finance research for designing flood risk and hazard maps methodologies sometimes based on complex algorithms and expensive modelling methods. It is therefore necessary to achieve know-how transfer towards developing countries and to adapt methods to their concrete socio-economic and environmental constraints.

The semi-arid environment might represent such a constraint: few methodologies specifically address this environment. Qualitative hazard mapping methodologies were developed in Mediterranean countries (France, Spain) mainly on a hydro-geomorphic basis (see for example Ballais et al. 2011, Marquès & Furdada 2012). Hydro-geomorphic methods have proved to be very suitable to the semi-arid and Mediterranean environment. These methods mainly assess hazard related to different components of a floodplain as it is ascertained that specific floodplain parts correspond to specific return period floods (Ballais et al. 2011). Yet, quantitative hazard assessment is necessary for further planning and protection measures especially in urban areas: therefore, methods that combine hydro-geomorphic approaches and hydraulic modelling are needed.

In semi-arid piedmont areas, hazard is frequently related to flash floods originating in steep mountainous catchments that affect often urbanized alluvial fans and piedmont aprons set at their outlet. High-energy catchments produce very rapid hydrological responses to short and intense rainfall events typical of that region. At the outlet of these catchments, the gently sloping alluvial fans and aprons offer no confinement to flood waves, thus floods can propagate. Hydro-geomorphic methods as well as classical modelling yield poor results in these environments. Fast urbanization on semi-arid piedmonts, and aggravating hazard situations have increased interest for specific methods in the United States where alternative methods to the FEMA model were sought (NRC 1996, Robins et al. 2009). In conclusion, specific methods for assessing flood hazard on semi-arid piedmonts are poorly developed, yet essential for providing sound basis for flood risk mitigation in the concerned areas.

The Moroccan approach to flood hazards is well summarized by the Water Act text cited above: infrastructure is needed for flood protection. This approach, close to the engineering paradigm (see Box 1-1) is probably related to a shorter experience with flood hazards. Indeed, until recently, drought was the main concern for Moroccan authorities and water scarcity was dealt with by important accumulation dam constructions (Taleb 2006). One could assert that the engineering approach was transferred from the water management to the hazard management domain. In the law and the resulting policies, water is mainly considered as a resource defined by its quality and quantity and much less as a dynamic element of hazard. For better flood hazard management, the reconsideration of water’s dynamic character in water management policies is needed.

Catchment agencies are responsible for the hydrologic studies intended for flood hazard assessment and mitigation. These agencies are poorly open to collaborations with the scientific and academic environment, impeding local innovation to occur in the hazard assessment field. Moroccan experience with hazard or risk mapping is virtually inexistent, except for the Al Hoceïma project cited above, that was mandated by regional authorities and realized according to French methods (IMS-RN 2011). Additional flood mapping studies were led in Morocco in the academic environment with no echo at the political level (Taous et al. 2010). We suggest this project represents a good example of improved collaboration between water managers and the academic field for better flood hazard identification, assessment, and mitigation.

Finally, at the implementation level, one may note that Morocco does not yet provide a legal framework for addressing flood hazard and risk from a planning point of view. A preliminary report on the Moroccan progress towards achieving the Hyogo priorities reflects clear deficiencies in disaster risk management (Chalabi 2010) especially in the prevention and planning fields. For instance, building codes only take into account seismic risk (MATUHE 2001a), while local development plans do no address hazard or risk. Yet, at the local level and in an unofficial way, water managers and urban planners make efforts to integrate flood hazard assessment to the planning documents (Werren 2013). A new urban code is also expected to account for flood hazards in the planning guidelines (oral information, Beni Mellal urban agency). We suggest that this study represents a step towards integrating the principles of the HFA within the Moroccan risk management, as hazard assessment and maps, as well as their implementation to planning are part of the HFA priorities.

To summarize, knowledge transfer in flood hazard assessment and mapping by adapting the well-established Swiss hazard map methodology (Loat & Petrascheck 1997, Kunz & Hurni 2008) to the Moroccan socio-economic and environmental specificity, and its further implementation in hazard-aware planning can be a valuable asset in achieving the Hyogo disaster risk prevention goals Morocco has committed to.

1.3. Problem

1.3.1. Research objectives and questions

This study's scope considers flood hazard assessment and mapping as a prevention tool for mitigating flood risk by diminishing communities' spatial exposure to flood hazards. Well-established hazard assessment methods like the Swiss flood hazard map model could improve developing nations' resilience to flood hazard provided they are adapted to local specificities and effectively implemented in land use management. In a context of know-how transfer and academic cooperation, this research examines **necessary methodological adaptations** hazard mapping that respond to local specificities and potential further **hazard map implementation** for disaster risk reduction in a typical semi-arid urban area of a developing country such as Morocco. Several research objectives are to be attained in order to respond to this study's basic questioning.

This study, mandated by the SDC, aims to **design**, by adapting the Swiss hazard assessment and mapping method, **an indicative danger map** intended to the use of local authorities, planners and water hazard managers on the study site. Moreover, the potential map implementation discussed in this thesis is presented to local stakeholders as a set of recommendations for further use in flood hazard management. In conclusion, three lines of objectives are to be attained. A **methodological** research aims at defining the best-suited adaptations of the Swiss method to the Moroccan context. An **institutional** research aims at exploring the possible implementation of the map to planning in order to mitigate risk. Finally an **applied** research aims at identifying and characterizing the conditions for knowledge transfer within the adaptation process.

Thus, this research pursues a **methodological** objective i.e. to develop a flood hazard mapping approach by adapting the Swiss hazard map method to the climatic and hydro-geomorphic specificities of a Moroccan study site. In a broader vision, this study seeks to come up with a cost-effective hazard assessment and mapping approach suitable for similar semi-arid, developing countries contexts. In order to attain this methodological objective, this study needs to answer several questions:

1) First, what adaptations are necessary to transpose the Swiss hazard assessment method developed in a temperate country to the **semi-arid piedmonts environment**? Indeed, the semi-arid hydro-climatic region produces different catchment behaviour and response and this variation may highly influence flood hazard assessment.

2) How can we assess hazard in a qualitative and quantitative manner in a situation of **poor data availability** and respond to the cost-effectiveness criterion that would guarantee this method's dissemination in developing countries?

3) Finally, at what degree this method is adaptable to the new context and which are the **elements of difficulty** for method adjustment?

Hazard maps play an effective role in flood risk mitigation once they are implemented to the flood risk management. Thus this research has an **institutional objective** related to the role of hazard assessment and mapping in the flood risk management process. In this study, we suggest a set of recommendations related to hazard maps implementation. We question two institutional aspects: the legal framework and the existing natural hazard management institutions.

1) In the present **legal framework** related to natural hazards in general and floods in particular, what could be the place of hazard maps as flood risk mitigation tools especially in the context of the new developments in risk management related to the Hyogo Framework for action?

2) The role of **institutional stakeholders** (e.g. planners and water managers) may be crucial for effective flood risk mitigation at the regional and local level. What are their effective roles in management and how could these roles be rethought in the sense of an integrated risk management approach?

3) In particular, what is the institutional stakeholders' approach to **flood hazard mapping** and maps implementation?

This is **applied research** from a cooperation project for knowledge transfer in flood hazard mapping; its scope is essentially practical yet based on theoretical considerations. Two questions related to the applied aspect of this research arise:

1) What are the best-suited knowledge transfer strategies for making this study's project acceptable and replicable in the selected context? Is academic collaboration an asset in knowhow transfer?

2) How do end-users, managers and the public perceive the adapted map and the way hazard information is encoded within?

1.3.2. Research design and plan

As stated above, this study aims to attain a practical objective, i.e. to adapt the Swiss hazard mapping method to a specific Moroccan site in order to come up with a cartographic document and a mapping method suitable for similar settings. An institutional objective questions the methodological implementation in disaster risk management.

In Chapter 2 we outline the conceptual framework related to disaster risk management and the notion of risk, in order to contextualize this study's scope. Therein, we present the Swiss hazard assessment and mapping procedure as a part of the integrated risk management approach.

Chapter 3 presents the spatial context of this study, represented by the flood hazard prone Beni Mellal urban area and the catchments that actually produce flood hazard.

Then, in the line of this study’s methodological objective, we undertake hazard map design for the chosen study site and discuss knowhow transfer and the necessary adaptations to the semi-arid piedmont environment and the Moroccan socio-economic context. Hydro-geomorphic mapping, hydrological and hydraulic modelling approaches are necessary in order to assess flood hazard and design subsequent flood hazard maps; chapters 4, 5 and 6 present each step in its scientific context and the necessary adaptations of available methods that respond to the study site’s specificity. Results are discussed in the light of the above-stated problematics.

This study’s final product, i.e. the indicative flood hazard map of Beni Mellal is further presented in chapter 7 and its implications for flood hazard management are discussed in the local context. Moreover, dissemination of the indicative flood hazard map method in similar locations is examined.

Integrating flood hazard maps to flood hazard management strategies requires adapting legal frameworks and institutional stakeholders participation. In chapter 8 we analyse these aspects from the point of view of the institutional vulnerability and its consequences in management. Concretely, we depict the present hazard management on the Beni Mellal study site and emphasize those aspects that hinder integrated risk management. This study’s second end product is presented here as a set of recommendations related to the adoption of hazard maps and their implementation, and improvement of local practice in hazard management. We equally explore risk management in Beni Mellal from a knowledge management perspective in order to better comprehend the existing conditions for transferring knowledge.

Chapter 9 draws this study’s general conclusions in order to reflect the above-set research questions and explore potential research perspectives.

2. Theoretical framework

In this chapter we present the basic concepts related to flood hazard assessment and risk mitigation as well as the driving risk approach applied in this study, i.e. integrated risk management. Then we exemplify the application of hazard assessment and mapping according to the integrated risk approach in Switzerland. Finally we briefly outline the conceptual context of knowledge transfer, i.e. knowledge management approaches and discuss the convergence of risk and knowledge management frameworks.

2.1. Integrated risk management

2.1.1. Definitions and concepts

The risk equation

The risk concept originates in the probability law. As stated in Section 1.1, in environmental studies, hazard, vulnerability and risk are related by the risk equation (1.1):

$$R = H * V \tag{1.1}$$

Where R = risk, H = hazard, and V = vulnerability.

This conceptual relationship's scope is primarily operative as it implies the possibility to actually quantify risk via mathematical computations for further risk management and planning. Yet, each of the equation's terms is fuzzy and difficult to measure (Dauphiné 2001, Wisner et al. 2004, Birkmann 2006) leading some authors to prefer a representation of risk as a function of hazard and vulnerability (equation 1.2, Dauphiné 2001):

$$R = f(H, V) \tag{1.2}$$

Hazard

First, the **hazard** concept is difficult to delineate from risk. If for some authors risk is primarily defined as the probability of a threatening event to occur (Tobin & Montz 1997, Smith & Petley 2009), for others, hazard itself is defined by its probability to occur and magnitude in time and space (Dauphiné 2001, Nott 2006). The difference may be related to the role vulnerability plays in the construction of the risk concept: that is, whether the term V of the risk equation is included to hazard as the *exposure* to a threatening event or phenomenon or whether it is considered in the equation term *per se*. Moreover, the second definition is more suitable for quantifying natural hazard and is often used in risk assessment procedures (e.g. Nott 2006).

The difficulty of delineating hazard from risk or vulnerability may be explained by the evolution of the hazard concept in environmental studies. Indeed, hazard was synonym of "threat" and "harm" to humans in early natural hazard studies (for example Burton

& Kates 1964) to gradually adjust its semantic extent towards the comprehension of the human system's role in "natural" hazard development (Tobin & Montz 1997, Alcántara-Ayala 2002). The threatening aspect of natural hazards still marks the concept's definition today, as Smith & Petley (2009) define environmental hazards as "all the potential threats facing human society by events that originate in or are transmitted by the environment".

Hazard requires quantification for practical purposes related to societal development and planning. Therefore measurable hazard is computed as a function of its probability of occurrence and its intensity (Dauphiné 2001, Nott 2006). There are specific hazard assessment procedures according to hazard types (e.g. floods, landslides or avalanches).

Vulnerability

The **vulnerability** term was introduced in environmental disaster-related studies by the so-called behaviourist or ecologist school that primarily addressed vulnerability as the exposure to harm (White 1973, Burton et al. 1978). Studies on environmental disasters in developing countries emphasized the importance of vulnerability in risk definition as well as its conceptual complexity (Cardona 2003, Wisner et al. 2004, Birkmann 2006).

Vulnerability is primarily associated with the potential to experience harm and thus can be quantified as the potential damage to assets, people or the environment (D'Ercole 1994, UNISDR 2009, Thomi 2010, Figure 2.1). Nevertheless certain damages are not measurable (psychological damage for example) and others pose an ethical problem (e.g. pricing human life). This analytical (Dauphiné 2001) concept of vulnerability is nevertheless used for assessing risk in a quantitative way in development planning and the insurance industry.

In a more dynamic and human-centred view, vulnerability is a dual concept composed of the **exposure** to harm and **coping capacity** as a vulnerability-reduction trigger (Dauphiné 2001, Wisner et al 2004, Figure 2.1). Exposure or susceptibility to hazards can be physical in space and time, i.e. people and assets potentially find themselves in the action range of a threatening natural phenomenon as for example people living on floodplains. Yet, **susceptibility** can be social, economic or institutional, all elements that hinder people or communities' capacity to cope with hazard consequences. Typically, it is axiomatic that poor and marginalized people, women, children or elderly persons are more exposed to harm during hazardous events (Tobin & Montz 1997, Dauphiné 2001, Wisner et al. 2004, Birkmann 2006, Smith & Petley 2009, etc.). The UNISDR definition of vulnerability is closer to the susceptibility concept ("The characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard") and is considered to be independent of exposure to hazard (UNISDR 2009).

In order to characterize and assess vulnerability in its complexity, several authors propose to study its different aspects (physical, socio-economic, political, institutional, cultural, etc.) using a taxonomic approach (Wilches-Chaux 1989, Aysan 1993, Alcántara-Ayala 2001, Birkman 2006, Menoni et al. 2012, Lorenz 2013). Vulnerability taxonomies provide tools to researchers and practitioners and help clarify the commonplace term "vulnerability" (Wisner et al. 2004). Moreover, vulnerability can be analysed as a dynamic aspect of risk, related to local unsafe conditions as well as to global root causes (Pressure and Release model: Blaikie et al. 1994, Wisner et al. 2004). Studies developed by LA RED (*Red de Estudios Sociales en Prevención de Desastres en América Latina*) emphasized the fact that vulnerability is socially and politically constructed and proposed to assess vulnerability in all its aspects in order to assess risk (Wilches-Chaux 1989, Maskrey 1997, Cardona 2003).

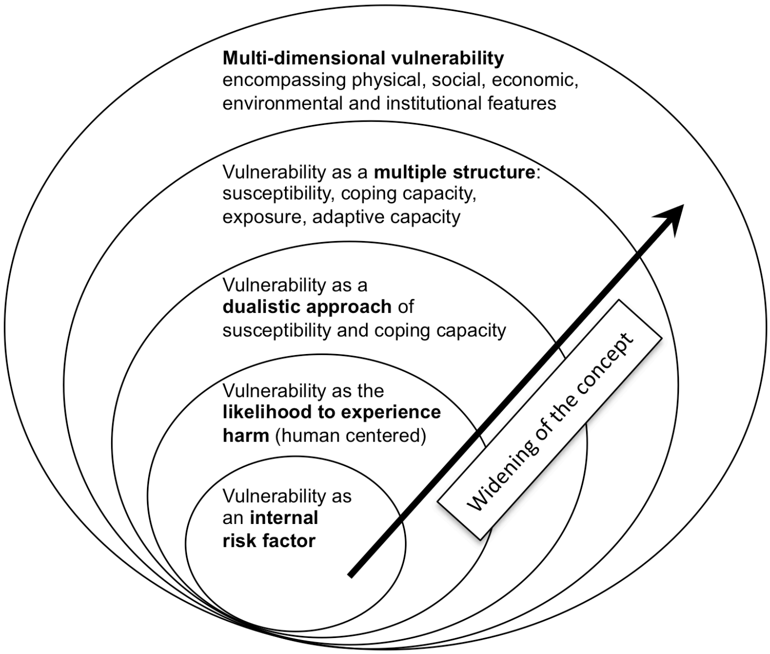


Figure 2.1. The conceptual spheres of vulnerability (after Birkmann 2006)

The psychology-based coping concept represents the capacity to respond on the short term to an induced stress at the livelihood level while **resilience** represents the capacity to absorb change on the long term (Davies 1996, Alwang et al. 2001). More complex vulnerability models structure the concept around susceptibility, coping, physical exposure and resilience (Bollin et al. 2003, Birkmann 2006, Figure 2.1) in order to comprehend the multiple individual and social dynamics related to vulnerability. In recent literature, resilience is thought as embedding coping and adaptive capacities (Kuhlicke 2013, Lorenz 2013).

Conceptual complexity is not fully covered by usual vulnerability indicators used in applied studies, development projects, or planning (Cardona 2003, Menoni et al. 2012). In risk assessment, vulnerability can be quantified as described above by measuring potential losses related to a hazardous event, with the limitations depicted above. Finally, for planning purposes of hazard and risk mapping, the spatial component of vulnerability is essential; thus, physical, spatial exposure to hazard represents the main vulnerability assessment needed when mapping risk.

Risk

Risk related to environmental hazards is essentially defined by a potential state; it represents the likelihood of an event to occur and not its realization (Tobin & Montz 1997, Cardona 2003, Smith & Petley 2009). Risk is also a composite concept highly dependent on the degree to which natural hazard and vulnerability semantics are clarified. There are two main approaches to risk (Thomi 2010): an **operationa**l one that seeks to quantify risk using the risk equation and a more **psycho-social approach** that takes into account on one hand risk subjectivity and on the other hand the socio-economic, political and institutional context that defines risk (Renn 1992a, 1992b).

Practitioners often use the operational definition of risk as the product of hazard and vulnerability (Dauphiné 2001) or "the combination of the probability of an event and its negative consequences" (UNISDR 2009). Thus, disaster risk, when measured, represents "the potential disaster losses, in lives, health status, livelihoods, assets and services, which could occur to a particular community or a society over some specified future time period"(UNISDR 2009). One can notice that in this approach, vulnerability is addressed as a synonym for exposure, inducing therefore a semantic narrowing of the resulting risk term. The measuring unit is difficult to clarify, as potential losses are diverse and sometimes immaterial (Dauphiné 2001). Nevertheless, in practice risk is often monetized. Computed probabilities of occurrence related to the realization of a hazardous event impact directly the computed risk monetary value.

More socially-oriented approaches rewrite the risk equation focussing on causes of vulnerability, considered as the risk trigger by excellence. For example, the Pressure and Release (PAR) disaster risk model (Wisner et al. 2004) denotes unsafe conditions (exposure and socio-economic and institutional susceptibilities), dynamic pressures related to socio-economic trends and root causes situated at the political level. In this approach, hazards become a generic term, while vulnerability is analysed in-depth.

From a psycho-social point of view, risk is a matter of perception (Dauphiné 2001, Cardona 2003) and its magnitude is closely related to individual subjectivities (Thomi 2010). Cultural, social and economic contexts, as well as personal values and experience with risk impact greatly the importance individuals give to risk. For example, the fact of living in a hazard prone area activates important cognitive dissonance reduction mechanisms that allow individuals to actually "live with risk" (Schoeneich et al. 1997, Schoeneich & Busset-Henchoz 1998). Beyond scientific risk assessment, understanding risk perception is essential for defining what is "acceptable risk" for a community or society (Dauphiné 2001).

Risk management versus risk reduction

In practice, the conceptual framework related to risk is implemented in management strategies in order to mitigate risk. Disaster risk management is defined by the UNISDR as "the systematic process of using administrative directives, organizations, and operational skills and capacities to implement strategies, policies and improved coping capacities in order to lessen the adverse impacts of hazards and the possibility of disaster" (UNISDR 2009). This definition underlines an institutional setting of measures undertaken in order to reduce risk. The definition of disaster risk reduction explains how disaster risk management approaches this goal: "the concept and practice of reducing disaster risks through systematic efforts to analyse and manage the causal factors of disasters, including through reduced exposure to hazards, lessened vulnerability of people and property, wise management of land and the environment, and improved preparedness for adverse events" (UNISDR 2009). Obviously, effective management actions are directly dependent on the way hazard, vulnerability and thus, risk are assessed.

2.1.2. Integrated risk management and the risk cycle

The integrated risk management approach reflects the Hyogo Framework for Action goals (SDC 2008). Risk reduction strategies are built around a hazardous event as a series of disaster response, recovery and mitigation of future risks (Figure 2.2). As shown in Figure 2.2, the strategy's three facets are equally balanced and interrelated as each phase should prepare the next one (for example, recovery must be started during the response stage) (SDC 2008). Moreover, risk reduction measures undertaken in integrated risk management need to be sustainable: "economically effective, socially acceptable and environmentally friendly" (Zimmermann et al. 2005).

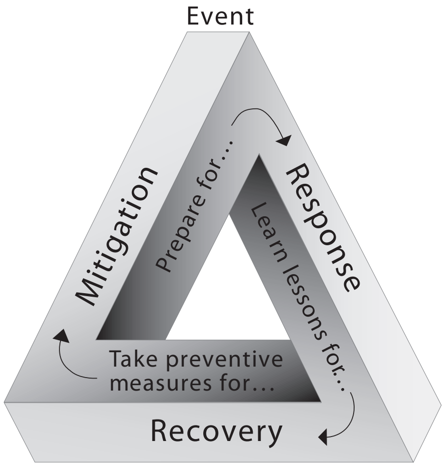


Figure 2.2. Integrated risk management approach (from SDC 2008)

For practical reasons, a more explicit representation of this framework is found in literature under the form of a "risk cycle" that represents risk reduction measures as a sequence of actions taken before and after a given hazardous event (e.g. Loat & Zimmermann 2004, ARE, OFEG, OFEFP 2005, Kienholz 2005). In the risk cycle presented below (Figure 2.3), from Kienholz (2005), mitigation measures are detailed in two types of actions: risk assessment and effective prevention measures as for to emphasize the importance of risk and hazard assessment in risk reduction strategies.

Risk assessment (Figure 2.3) is undertaken prior to a given event but results from lessons learned from past events (Reynard et November 2008, Reynard et al. 2008). It consists of scientific risk analysis and further evaluation (public negotiation of risk acceptability and protection needs determination). The risk **analysis** stage mainly concerns scientific hazard assessment following politically defined guidelines and thresholds, and the analysis of the exposure to hazards. The risk **evaluation** stage is a political decision-making process where public negotiation is essential.

Figure 2.3. The risk cycle (from Kienholz 2005).

Actual **mitigation** (Figure 2.3) measures consist of preventive actions that can be structural or non-structural and disaster preparedness (for example pre-alert systems, evacuation plans). In a strict sense, **structural measures** refer to protective constructions and infrastructure (for floods: dams, dikes, etc.); more generally they comprise all those preventive actions that impact and directly mitigate hazard (Loat & Petrascheck 1997), as for example catchment reforestation or river floodplain restoration for flow excess absorption. **Non-structural measures** address vulnerability (Loat & Petrascheck 1997) by increasing resilience (awareness, insurance systems, policies) or mitigating exposure (land use planning in accordance to the hazard situation, early-warning systems) (SDC 2008). Hazard assessment and mapping is generally undertaken during this stage.

The disaster **response** phase (Figure 2.3) is detailed as an emergency relief stage followed by the restoration of functional structures in a community (economy, institutions) in preparation for the recovery phase. This stage represents a "window of opportunity for enduring change" (SDC 2008) in the sense that new policies, public commitment and strengths can emerge during this critical period (SDC 2008, Kuhlicke 2013).

Finally, the **recovery** phase (Figure 2.3) deals with hazard-aware reconstruction that should create better coping capacities and avoid crafting new risks (SDC 2008)

The scope of this study extends to risk analysis during the assessment phase and particularly to hazard assessment and mapping for planning purposes according to the

Swiss hazard mapping methodology. This assessment's results however impact the whole risk cycle: mitigation measures of land-use planning or protective measures for exposed areas; preparedness via evacuation maps; hazard-aware restoration and reconstruction. In the next section we outline the Swiss approach to hazard assessment that is based on the integrated risk management framework.

2.2. Hazard assessment and mapping in Switzerland

2.2.1. Historical and legal background

As an alpine country, Switzerland's territory was historically exposed to multiple hazards: snow avalanches, landslides and rockfalls, debris flows and floods. Among these hazards, floods from rivers and lakes were particularly damaging be it by the direct effect of water excess, the destruction related to sediment transport and deposition, or the waves of illness resulting of water stagnation in valley bottoms and lowlands after important flood events (Vischer 2003).

Until the 19th century, the concerned communities undertook localized protection measures against specific rivers or torrents; yet the creation of the modern Swiss federal state in 1848 stimulated the emergence of greater flood protection projects aimed at reducing river impacts on floodplains and gaining new space for agriculture. The alpine Rhine River rectification (1862-1900), as well as the first Rhône River rectification (1863-1894) represented such large projects that were made possible by the newly created Swiss Confederation's financial involvement (Vischer 2003). At the same time, increasing awareness about the impact of deforestation on flood outbreak and aggravation defined forest protection and catchment management as the second panel of flood protection strategies in Switzerland. The Forest Act (1876) and Water Management Act (1877) set the legal framework for flood hazard management in Switzerland based on structural flood protection measures and flood mitigation via protective forests and catchment management (Reynard et al. 2000, Varone et al. 2002, Vischer 2003, SDC 2005).

Despite massive investments in protection works on the entire territory, the flood disasters that struck Switzerland in 1987 deeply questioned the national flood hazard strategy (Zaugg 2004): structural works failed to protect from floods while offering a false sense of security.

While the Land Use Planning Act (*Loi fédérale sur l'aménagement du territoire,* LAT, 22.06.1979, RS[2] 700) already stipulated that planning must account for territory-related hazards (Sections 1, 6, 7), a new strategy in natural hazard management emerged since 1991 with the new Forest Act (*Loi fédérale sur les forêts*, LFo, 4.10.1991, RS 921.0) and Water Management Act (*Loi fédérale sur l'aménagement des cours d'eau*, LACE, 21.06.1991, RS 721.100) and their respective decrees published in 1994 (*Ordonnance fédérale sur les forêts*, OFo, 30.11.1994, RS 921.01 and *Ordonnance fédérale sur l'aménagement des cours d'eau*, OACE, 2.11.1994, RS 721.100.1) (Loat & Petrascheck 1997, Lüthi 2004, ARE, OFEG, OFEFP 2005).

[2] RS (Recueil systématique des lois suisses) : Swiss laws systematic collection.

The new Swiss approach to natural hazard management reflects the findings of the United Nations International Decade for Natural Disasters Reduction (IDNDR) in that it aims at creating a risk culture through integrated risk management approaches (SDC 2008).

Thus, the new Swiss policy for hazard management postulates the priority of preventive land use planning over structural protection works (LACE 1991, Section 3). Indeed, despite important territorial constraints related to the country's small surface and mountainous topography, hazard-aware land use planning is necessary in order to reduce vulnerability and avoid massive damage (ARE, OFEG, OFEFP 2005). Yet, already built areas exposed to natural threats are provided with suitable structural protection. Threat related to natural hazards is considered as a property of a given territory and therefore it may impact or even proscribe specific land uses (Loat & Petrascheck 1997). Hazard assessment and mapping is hence essential in order to characterize a territory and its possible land uses.

The basic document that accounts for natural hazards for land-use planning activities in Switzerland is the **danger map**, defined as "mapping based on a set of strictly objective and scientific criteria containing the following information for the entire territory and in a clearly defined investigation perimeter: threat or absence of threat for each portion of territory, hazard type, risk intensity and probability"[3] (Lüthi 2004, our translation). We discuss in the next sub-section the specificity of a danger map as compared to hazard maps.

The 1991 federal laws on forests and river management, detailed in the 1994 related decrees entrust flood hazard protection to the Swiss cantons (LACE 1991, Sections 2, 3, and 6, Lfo 1991, Section 36) and enforce danger maps as compulsory (OACE 1994 Section 27, OFo 1994, Section 15). The cantons are required to design danger maps according to federal guidelines. Therefore, the Swiss hazard assessment and mapping procedure is uniform throughout the country. The Natural Hazards PLANAT platform is an advisory body composed of government members, natural hazard experts and practitioners. PLANAT was created in order to coordinate and implement the new policies in the sense of an integrated risk management that fulfil the Hyogo goals.

2.2.2. The Swiss danger maps in practice

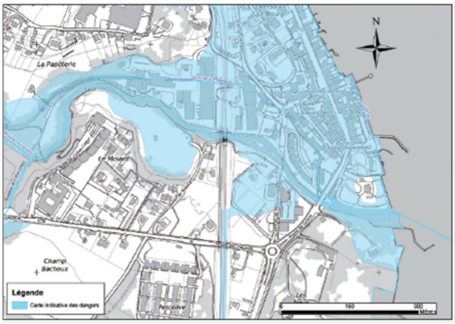
Hazard maps assessing primarily the avalanche threat were designed in Switzerland since the early 1970[s] (SDC 2005), but the hazard assessment effort was first implemented at the national scale by the 1998 laws on forests and river management, reflecting the change in risk management paradigm. The cantons were requested to produce danger maps for the whole territory by 2014. Today, danger maps related to the avalanche threat are available for 97% of the territory, water related threat maps for 85%, rockfalls and landslide-related threat maps for 82% and 76% respectively

[3] « une cartographie établie sur la base de critères rigoureusement objectifs et scientifiques comportant les indications suivantes pour l'ensemble du territoire, dans un périmètre d'investigation clairement délimité: menace ou absence de menace pour chaque portion de territoire, type de dangers, intensité et probabilité des risques » (Lüthi 2004).

(ARE 2013). Switzerland adopted a multi-hazard approach as each type of hazard is assessed separately following objective criteria. Then, hazards are synoptically represented using a uniform legend for a given territory. The federal authorities produced guidelines for the cantons to assess the concerned types of hazard (avalanches, floods and debris flows, and gravitational hazards) in a unitary manner throughout the national territory (OFF 1984, Lateltin 1997, Loat & Petrascheck 1997).

Map types: hazard versus danger maps

Swiss danger maps are technical, scientific documents that inform about the presence or absence of threat related to natural hazards within a given territory: they have no inherent legal enforcement (ARE, OFEG, OFEFP 2005). Their findings are enforced only when these documents are implemented to specific hazard management measures (planning, structural measures or emergency plans (Loat & Petrascheck 1997, Lüthi 2004, ARE, OFEG, OFEFP 2005, Penelas et al. 2008). In land use planning, three types of cartographic documents are used in Switzerland as a base for planning documents: the hazard indication maps, danger maps and hazard intensity maps.



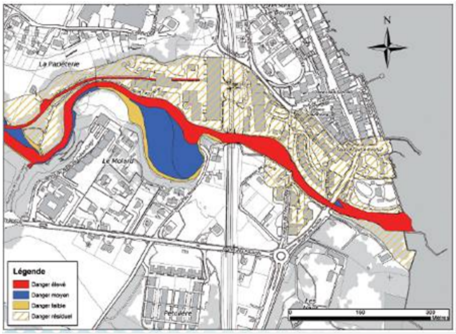


Figure 2.4. Example of flood hazard indication map determining the maximum extent of an extreme flood, Geneva, Switzerland (from http://etat.geneve.ch/dt/eau/carte_indicative_dangers).

Figure 2.5. Example of flood danger map, Geneva, Switzerland. Each zone represents a danger degree and land use prescription: red (high threat) = building prohibition zone; blue (medium threat) = building conditions zone; yellow (low threat) = awareness zone; white-yellow (residual threat) = awareness zone (from http://etat.geneve.ch/dt/eau/cartes_dangers).

Hazard indication maps are designed for large territories, generally a canton's surface, at relatively small scales (1:10'000 – 1:50'000). Their primary role is to offer a general view on hazards concerning a given territory and to determine possible conflicts between land use and natural hazards that would require more detailed assessment (ARE, OFEG, OFEFP 2005, Figure 2.4). Hazard indication maps may encompass spatial and content inaccuracies; they provide little detail on hazard intensity or probability of occurrence, and they do not contain land use prescriptions. They form the basic technical document for the cantonal land-use plans (*Plans directeurs cantonaux)*. The Swiss hazard indication maps are equivalent to

susceptibility maps in literature, as they aim at identifying those areas with a propensity to be affected by a hazardous phenomenon based only on the terrain conditions, without taking into account the probability of occurrence of the dangerous phenomenon (Soeters & Van Westen 1996, Guzetti et al. 1999, Santangelo et al. 2011). Susceptibility maps can be direct, when they result from field mapping or indirect, when they result from modelling (Soeters & Van Westen 1996).

Danger maps are designed at the municipality level for map scales of 1:2’000 – 1:10’000. They provide detailed spatial and scientific information on the natural hazards threat in terms of hazard intensity and probability and contain a set of land use prescriptions related to each hazard degree (Figure 2.5). In the natural hazard literature, Swiss danger maps could be equivalent to **hazard maps**, as they account for the hazardous event’s magnitude and probability of occurrence (Soeters & Van Westen 1996). Nevertheless, by providing specific land use prescriptions, danger maps go beyond the scope of hazard analysis to actually evaluate risk and propose adequate mitigation measures (see the risk cycle, (Figure 2.3). Therefore, danger maps could be considered as complex hazard maps or basic risk evaluation documents. Danger maps form the basis for municipal land-use plans and ensue in building regulations.

Danger to people, animals and infrastructure related to natural hazards is computed as a function of hazard intensity and probability according to the Swiss hazard matrix. A detailed description of the hazard matrix and its signification is provided in Chapter 7, Section 7.1.1).

Hazard intensity maps represent hazard intensity information following specified hazard thresholds and for selected recurrence probabilities. These typical hazard assessment documents play multiple roles within the risk management process. First, intensity maps integrate the danger map design, as danger degrees are computed as a function of hazard intensity and probability. Moreover, these maps are used for dimensioning protective structures in already built areas (ARE, OFEG, OFEFP 2005). Finally, these maps may prove more transparent to the public than danger maps and hence represent good communication tools.

Map type: international	Swiss system
Past event inventory	Past event inventory
Susceptibility map: indirect	Hazard indication map
Susceptibility map: direct	Phenomena map
Hazard map	Danger map Hazard intensity map
Risk map	Risk map

Table 2.1. Correspondence of flood maps in the Swiss and the international terminologies.

There are terminology differences between the Swiss system and the international literature on hazards. In Table 2.1, the correspondence of flood maps in the Swiss and the international systems is listed.

Danger maps: hazard or risk assessment tools?

As stated above, the Swiss danger maps go beyond sole hazard assessment. Indeed, unlike hazard indication and hazard intensity maps, that depict hazard in its spatial or dynamic aspects, danger maps address hazard as a function of the threat it represents to people, animals and infrastructure, and edict specific land use and building regulation prescriptions for each delimited danger zone. In a sense, danger maps operate partial risk assessment related to a given territory. Nevertheless, these are not risk maps, as vulnerability related to the mapped territory should be accounted in the risk assessment process.

The Swiss risk management approach addresses territorial vulnerability or exposure to natural hazards on the basis of danger maps in the risk evaluation phase. Indeed, in already built, hazard-exposed areas, an evaluation of the protection objectives is undertaken. Hence, the more sensitive or valuable the objects to be protected, the higher the level of required security is set (ARE, OFEG, OFEFP 2005). The required security level is assessed according to a protection objectives' matrix that crosses specific land uses and hazard levels. (OFEG 2001, ARE, OFEG, OFEFP 2005, Figure 2.6).

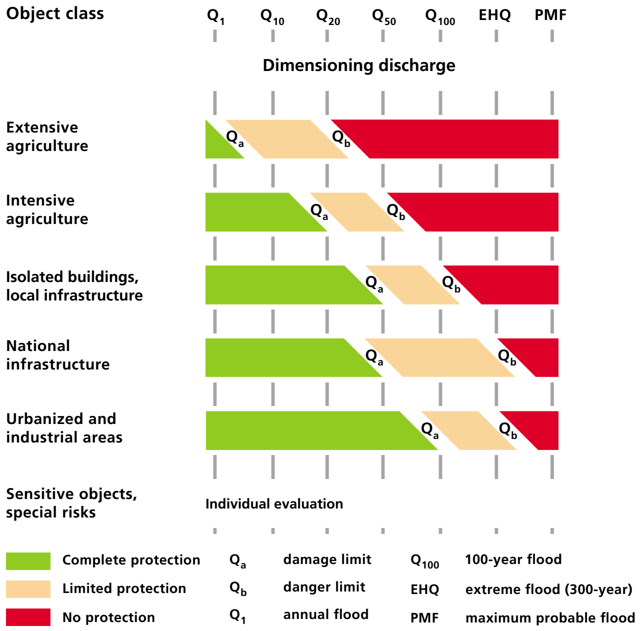


Figure 2.6. Protection objectives matrix for flood hazards. Translated from OFEG (2001).

This approach balances cost-effectiveness and protection requirements at the national level in a sense of social and environmental equity (ARE, OFEG, OFEFP 2005). By defining more or less clear thresholds for protection objectives, the Swiss approach provides a uniform and quasi-institutionalized risk acceptance pattern. Yet, in practice social negotiation is at the heart of hazard management strategies; therefore, the hazard assessment tools play also an awareness and responsibility-raising role.

Danger maps design workflow

Danger maps are composite documents that go beyond the hazard identification phase, as their findings are directly applicable in land use plans. Their design is nevertheless based on several documents and mapping approaches that are aimed at identifying and assessing threat related to natural phenomena on a given territory. First, detailed **inventories** of known **historical events** that impacted the studied area are undertaken in order to create a hazard knowledge database (Figure 2.7). The Swiss Confederation produced specific guidelines for data collection and inventory design (e.g. Loat & Petrasheck 1997). Hazard-related, **geomorphic mapping** of the studied area completes historical hazard identification (Figure 2.7). Geomorphic maps (called *phenomena* maps in Switzerland) offer a detailed spatial outline of the present hazards and all signs of past events that still mark the landscape (Kienholz & Krummenacher 1995).

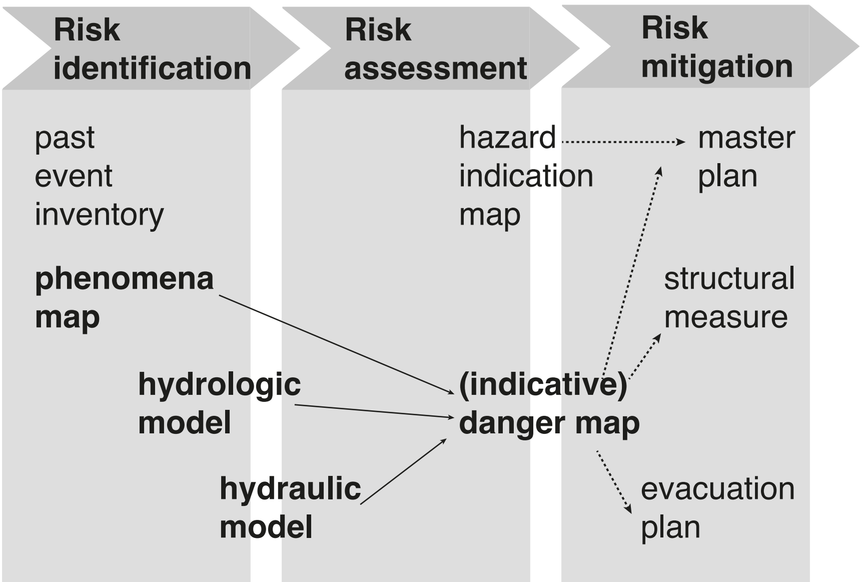


Figure 2.7. Hazard assessment and mapping workflow within the Swiss methodology, and their consequences on risk mitigation. In bold: documents and assessment produced in this project for the Beni Mellal study case.

Hazard assessment for planning and other mitigation purposes refer to rare event scenarios that may not have been field-monitored. Knowing that natural phenomena like floods or earthquakes present certain cyclical behaviour, the choice of the assessed events is based on the computed statistical probability of recurrence of an event. In order to assess these potential events, their intensity and spatial consequences, **model computations** are essential (Figure 2.7). In flood hazard assessment, two types of models are needed: **hydrologic models** that assess the potential flow discharge related to a given recurrence period event, and **hydraulic models** that compute the spatial impact of a given discharge flood, in terms of flood extent, water depth, flow velocity, and solid discharge behaviour. These computed elements form the basis for assessing the threat related to an event's consequences on people, animals, infrastructure or protective structures (Loat & Petrascheck 1997)).

Finally, the mapped hazard zones, in terms of probability of occurrence and hazard intensity are assigned **danger degrees** (low, medium and high) and specific land use prescriptions in order to mitigate spatial exposure to hazard in the studied area.

In this research, we follow relatively closely the presented workflow (Figure 2.7) in order to assess and to map flood hazard in the flood-prone piedmont city of Beni Mellal, in Morocco and more generally to adapt the Swiss hazard assessment and mapping methodology to specific semi-arid environments in developing countries. Moreover, in views of potential danger map implementation, we explore institutional vulnerability in Beni Mellal and knowledge management aspects related to the Swiss hazard assessment and mapping methodology adaptation.

Hazard assessment terminology

In order to keep trace of the adaptation process and the methodology transfer from the Swiss system abroad, this study uses the terminology established in Switzerland for flood hazard assessment and mapping. Nevertheless, we are aware of the correspondence between the Swiss terminology and the natural hazards literature and practice. The equivalence between the Swiss and the international system is listed in Table 2.1.

The Swiss methodology: advantages and limitations

Swiss danger maps have been produced since 30 years according to the 1991 policy on natural hazards that put an emphasis on passive risk mitigation measures. The practical application of the Swiss methodology, regulated by federal recommendations and guidelines, revealed strengths, but also limitations of the Swiss system. As no literature is available on this issue, the conclusions drawn below result form a series of interviews with natural hazards practitioners in Switzerland. A series of questions were set in order to identify the perceived advantages and limitations of the Swiss method, its transferability abroad as well as the potential of hazard maps as risk communication tools.

Homogeneous guidelines, based on uniform thresholds applicable to the entire territory and for several hazard types, represent the most important strength of the Swiss methodology. Moreover, the political will to emphasize passive mitigation measures, reflected in the enforcement of danger maps by implementation into land use planning documents made it possible to apply this methodology with enduring results. Danger maps represent essential documents that allow understanding and better regulating interactions between land use and natural hazards. Finally, these maps are thought to contribute at decreasing people's vulnerability to natural hazards.

Nevertheless, there is a recent trend in the natural hazards practice to shift from assessing hazards towards the assessment of risks (PLANAT 2011). Indeed, danger maps are thought to be effective only in the planning field, as they can justify development choices for a given territory according to the natural hazard reality (MZ 2013). Nevertheless, hazard maps are thought to be ineffective in other fields of risk management such as preparedness or structural mitigation. For example, danger maps cannot justify the use of structural mitigation measures, as they do not assess the decrease in damage related to protection objects such as dams or dikes. By not assessing vulnerability in a mapped territory, danger maps cannot quantify the decrease in damage that may result from the passive mitigation measures they proscribe (EB 2013, RG 2013). Therefore, the concrete outcome of the Swiss passive mitigation policy is difficult to assess.

Moreover, the practice has revealed certain inconsistencies of the methodology related to the colour code that are more broadly explained in Section 7.1.2. These inconsistencies persist, as no important modification of the initial guidelines has been undertaken. The relatively long time lapse between the first maps produced and the completion of the nation-wide mapping campaign resulted in maps that are different in their content as well as in their implementation. First, maps produced in the early 1990’s did not account for climate change effects, thus the scenarios they were based upon may be obsolete (EB 2013). Map updates were not undertaken throughout the territory. Then, the process of map design and the communication between designers, planners and the public have evolved over time and varied among different cantons or municipalities (EB 2013, RG 2013).

Regarding the communication of hazards and public risk perception, hazard maps are thought to have little effect on raising awareness on risks or changing people’s perceptions. Indeed, maps are unevenly made public among Cantons or municipalities, and as such they do not represent a risk communication basis. People seem to be more sensitive to short-term flood experience than to long-term forecasts as predicted by danger maps. The main public concern regarding danger maps is related to the effects these maps have on the tenure rights and subsequent consequences on real estate value (EB 2013, MZ 2013, RG 2013). Respondents considered that a community-based mapping process could improve people’s acceptance of danger maps; yet in practice, maps are designed by engineers and supervised by planners without involvement of local people in the process (EB 2013).

Finally, respondents note that the Swiss methodology is transferrable abroad, but it requires legal enforcing to become effective; thus, depending on local situations, danger maps may fail to achieve their role. Moreover, hazard mapping can be seen as cost-effective relative to structural mitigation measures, even though it requires specialized skills and precise data.

2.3. Knowledge management: theoretical background

This study has an applied objective concerning knowledge transfer by adapting the Swiss hazard assessment and mapping methodology to the Moroccan context. Knowledge transfer integrates the broader theoretical field of knowledge management we shortly outline below.

2.3.1. Knowledge management: definitions and processes

A few definitions

In an increasingly knowledge-driven society (Stehr 1996), knowledge management emerged in the economics field as a set of strategies that use and enhance an organization's **knowledge assets** in order to achieve competitive advantage (Alavi & Leidner 2001). Other knowledge visions complete the asset definition above. Indeed, as knowledge is inherent to individuals, it can be viewed as a "**state of mind**" (Alavi & Leidner 2001); therefore, knowledge management is expected to enable people's access to knowledge and its amplification by individuals in order to impact the organization's needs. Knowledge as a **process** (Nonaka & Takeuchi 1995, Gupta & Govindarajan 2000, Nonaka et al. 2008) is dynamically outlined by flows of knowledge creation and sharing where actors and relationships play an important role in knowledge enhancement. Moreover, knowledge can be viewed as a **capacity** (Stehr 1996, Alavi & Leidner 2001), thus knowledge management should focus on developing core competencies within the organization that would improve its resilience.

Polanyi (1967) theorized knowledge as a continuum of explicit, implicit and tacit parcels. **Explicit** knowledge is objective and rational; it can, therefore, be captured and represented; **implicit** knowledge is representable while **tacit** knowledge is inherent to the person, experience-based and thus difficult to articulate (Polanyi 1967, Nonaka & Takeuchi 1995, Nonaka & Von Grogh 2009).

Knowledge processes

Organizations are considered to be "knowledge systems" that undertake socially driven processes of knowledge creation, knowledge storage and retrieval, knowledge transfer and knowledge application for competitive advantage (Pentland 1995, Alavi & Leidner 2001).

Knowledge **creation** i.e the process of amplifying individual knowledge within an organization's knowledge system (Nonaka & Von Grogh 2009) is viewed as a fuel for innovation (Nonaka & Takeuchi 1995). Nonaka (1994), followed by Nonaka & Takeuchi (1995) conceptualized knowledge creation within an organization as a process of explicit and tacit knowledge conversion through knowledge **socialization** (tacit to tacit knowledge), **combination** (explicit to explicit knowledge), **externalization** (tacit to explicit knowledge) and **internalization** (explicit to tacit knowledge), see Figure 2.8. Innovation results from the spiralling aspect of knowledge conversion within the organization, that is, knowledge created sets the basis for further knowledge creation.

Knowledge **storage** and **retrieval** is related to an organization's memory. Annual reports, knowledge databases or Internet knowledge-retrieval platforms represent examples of knowledge storage processes.

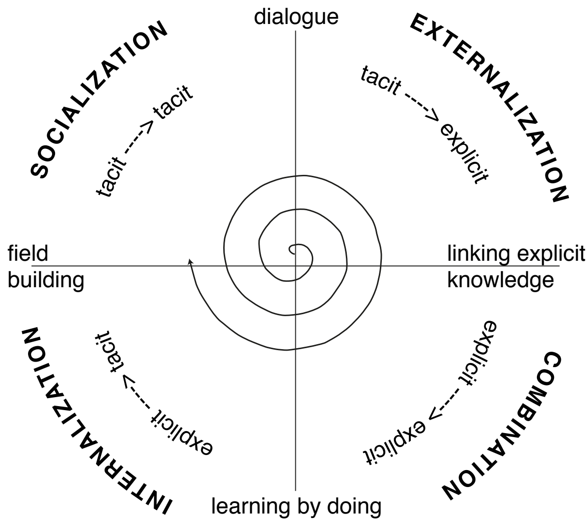


Figure 2.8. The knowledge creation cycle (Nonaka 1994, Nonaka & Takeuchi 1995).

Knowledge **transfer** represents the process of conveying knowledge within an organization or among different organizations. Basically, it can be included in technology transfer processes (Roberts 2000). Successful knowledge transfer depends on several factors: the perceived value of the knowledge to transfer will directly influence the knowledge source's willingness to share it and the receiver's willingness to acquire it, yet successful transfer is bound by the richness and quality of the transmission channels and by the receiver's capacity to absorb knowledge (Gupta & Govindarajan 2000, Alavi & Leidner 2001, see Figure 2.9). Cohen & Levinthal (1990) defined absorptive capacity as "the ability (…) to recognize the value of new, external information, assimilate it and apply it (…)". As shown in Figure 2.9, knowledge transfer is a function of communication (Roberts 2000, Kimble 2013) and cannot be achieved in a unidirectional manner. Know-how transfer refers to conveying tacit and explicit knowledge: Roberts (2000) states that the tacit aspects of knowledge can only be transferred by demonstration, or "show-how".

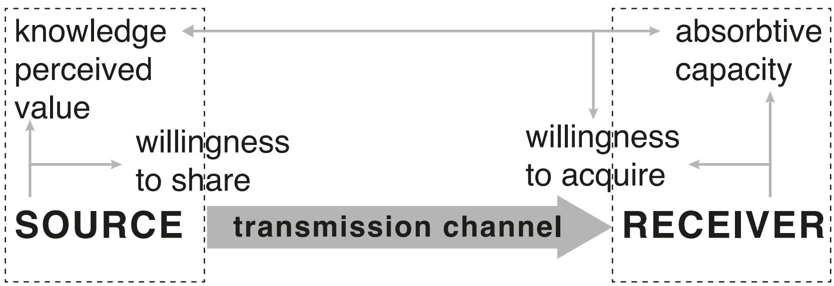


Figure 2.9. Successful knowledge transfer conditions. After Gupta & Govindarajan (2000).

Finally, newly created or transferred knowledge **application** refers to the way knowledge is used within an organization in order to improve its internal capabilities (Alavi & Leidner 2001).

Knowledge management applications

The most usual systemic knowledge management strategies are related to (1) coding and sharing the existing knowledge as best practice, (2) mapping the existent internal expertise, and (3) networking knowledge (Alavi & Leidner 2001)

Knowledge management and disaster risk reduction

Knowledge networks represent platforms for knowledge sharing and amplification. Knowledge management in the highly interdisciplinary disaster risk reduction field represents a relatively recent development. Its emergence is related to raising awareness that the substantial existent knowledge on risks, assessments and mitigation is useless if not properly codified and retrieved (Mohanty et al. 2004, UNISDR 2013).

The primary application of knowledge management in disaster risk reduction is related to **knowledge networking** that is, creating unitary platforms for knowledge creation, retrieval and sharing. For example in Switzerland, the PLANAT natural hazards platform may be considered as a knowledge networking platform, that not only retrieves and shares knowledge, but also impacts national policies on risk management.

Moreover, knowledge about risk in the affected communities, as well as within the risk management organizations plays a fundamental role in effectively mitigating risks. Several studies argued that risk perception is correlated with experiencing hazardous situations (Slovic et al. 2004, Siegrist & Gutscher 2006). In accordance to the availability heuristic (Tversky & Kahneman 1982), Siegrist & Gutscher (2006) also argued that risk perceptions and risk assessments correlate when people have experienced a hazardous event such as a flood. Thus, hazard maps are thought to enhance people's perceptions on the risk they are facing if maps systematically make risk information available, especially in those areas where no recent flood experience was made (Siegrist & Gutscher 2006). Nevertheless, the affective consequences of a flood, that were found to influence post-flood precautionary behaviour (Siegrist & Gutscher 2008) cannot be made available by maps, therefore hazard maps are only partial risk communication tools. Knowledge about risk covers a vast interdisciplinary domain, where economics-like knowledge assets are as important as the psychological processes of risk perception or risk knowledge creation. This study focuses on hazard maps design, adaptation and their possible implementation to planning. Therefore, our approach to knowledge is obviously more limited, and the knowledge management framework applies more particularly to institutional risk management.

2.3.2. Risk and knowledge management: two converging schemes

The integrated risk management scheme requires dealing with an important set of heterogeneous knowledge stemming from the scientific, technical, administrative, political, socio-economical fields, and more. Therefore, exploring risk management from the perspective of knowledge management approaches may provide useful insights in the way knowledge resources and their fluxes resulting of social interaction among risk management actors actually impact the risk management process and the overall resilience or inversely, vulnerability in a community. There are several converging points in the risk and knowledge management schemes that allow this double-sided interpretation grid.

First, knowledge is often defined as a **capacity** for action (Stehr 1996, Alavi & Leidner 2001), thus the capabilities resulting from knowledge allow an organization to become resilient and competitive. Integrated risk management on the other hand aims at strengthening coping capacities and resilience to hazards in order to mitigate risk. We argue that knowledge acquisition and application in the risk management domain represent the fuel for increasing a community's resilience to natural hazards.

Then, knowledge creation, resulting in improved capabilities is a social, networking **process** essentially based on the relationships between actors. The integrated aspect of risk management shares the same semantics of process integration, networking and information fluxes. In the highly multidisciplinary field of risk science and management, active processes of knowledge transfer are necessary, as the tacit aspect of knowledge is usually present and **know-how** transfer by demonstration (or "show-how") takes an important place.

Moreover, the integrated risk management scheme is **cyclical**, as is the knowledge creation process as theorized by Nonaka (1994). That is, action is often taken considering previous lessons learned, which could be translated, in the knowledge management language, as an internalization of knowledge in order to create new capabilities. Indeed, lessons learned and codified best practices in the risk management field are thought to increase overall resilience in a community.

3. Case study

3.1. Flood hazard issues

Climate change is believed to increase the seasonality of Mediterranean environments, superimposed on a sustained tendency to climate drying. It is also expected to induce more extreme hydro-climatic behaviours in orography-influenced regions (Giorgi & Lionello 2008, Magnan et al. 2009, IPCC 2012). In Morocco, climate change scenarios for 2020 predict, along with higher temperature and decrease of the average annual precipitations, "an increase in the frequency and intensity of frontal and convective thunderstorms in the North and the West of the Atlas mountains" and the concentration of the winter rainfall on a short period of time (MATUHE 2001b).

Since the year 2000, several flood disasters lead the Moroccan authorities to acknowledge flood hazard as a public security issue (BRL, ADI, Aquater 2004, UNDP 2006). Consequently, a flood hazard mitigation strategy was developed through the national Flood Mitigation Plans (*Plan national de protection contre les inondations*) and Hydraulic Catchment Agencies in charge of water management at the scale of Morocco's great river catchments were created (BRL, ADI, Aquater 2004).

The city of Beni Mellal, situated at the boundary of the Beni Mellal Atlas and the Tadla plain (Figure 3.1), is at the heart of the flood hazard problematic that arose in Morocco since the year 2000. Indeed, the national Flood Mitigation Plan designed the city one of the country's flood vulnerable points as several flood events were recorded there. Flood hazard and its consequences to the urban area result from the interplay of several factors related as much to the natural environment than to human activities.

High urbanization rates, urban sprawl and important territorial changes are thought to induce higher vulnerability to natural and human-induced hazards at the urban level (El Khalki et al. 2005). On the other hand, land cover changes, due mostly to deforestation, inappropriate agricultural practice, and land abandonment related to rural migration had an effective role in erosion processes increase in the uphill catchments that drain the city of Beni Mellal (El Khalki & Benyoucef 2005, Bachaoui et al. 2007). All these tendencies are embedded in the general climate change pattern (Werren et al. 2013) that is strongly perceived in Morocco as well as in the entire Mediterranean region.

3.2. Geographic setting

Beni Mellal, capital city of the Tadla-Azilal region, is set on the northern Atlas Piedmont, at the edge of the last Atlas elevations and the economically flourishing, irrigated perimeters of the Tadla plain (Figure 3.1). Some authors consider the Beni Mellal Atlas as the most southern chain of the Middle Atlas (e.g. El Khalki et al. 2005), while other authors (e.g. Bouachou 1997) include this massif to the High Atlas. The delimitation difficulty stems in a differentiation of geological and geographical boundaries as this massif is set at the limit between the two geologic domains (Monbaron 1981). The city historical nucleus lies on the piedmont (called *dir* in

Moroccan Arabic language), while the newer colonial and contemporary urban areas stretch on old quaternary alluvial fans that emerge at the outlet of four torrential catchments and extend to the lowlands of the Tadla plain. The city marks an important stop on the "royal road" linking Morocco's ancient capitals Fez and Marrakech.

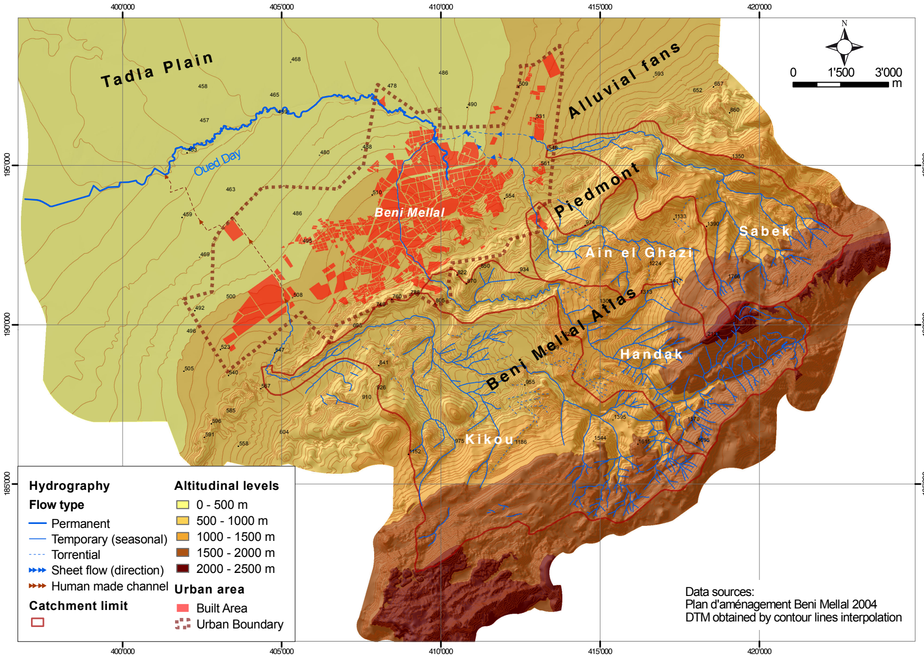


Figure 3.1. Study site geographic setting.

Figure 3.2. The Beni Mellal Atlas dominating the city (left) and view over Beni Mellal from the Atlas (right).

Four intermittent streams cross the urban perimeter of Beni Mellal. From E to W, the Sabek, Aïn el Ghazi and Handak streams drain small torrential catchments of 20.8 km², 15.8 km² and 29.7 km² respectively. They cross the city up to a junction point situated in its central-northern part where they meet the Day stream (Figure 3.1). At the western side of the urban perimeter, the Kikou stream drains a 54-km² catchment. Its floods endanger the industrial quarters of Beni Mellal (Figure 3.1). The four streams Sabek, Aïn el Ghazi, Handak, and Kikou have a seasonal flow regime regulated by winter rainfall and snowmelt. The next section presents the four catchments and their relationship, in terms of flood hazard, to the urban area. We present here their characteristics in 2010, date of validity of the indicative danger map. We justify this choice by the fast change pattern imposed by several flood mitigation structures in progress inside the urban perimeter (hazard assessment could hardly be adapted at the change pace) and by fast urban growth.

3.3. Geologic and hydro-geomorphic context

The city of Beni Mellal is set at the boundary between the Beni Mellal Atlas massif and the Tadla plain, on the northern Atlas piedmont. These three domains were individualized during the Atlas uplift dating from the Pontian-Pliocene (Monbaron 1981, 1982). The geologic history of this massif was first marked by a Jurassic distension phase related to the subsidence of an incipient Atlas rift that culminated during the Bathonian-Bajocian with a series of faulting and magmatic events. Then, a tectonically inactive period followed until the Pontian-Pliocene Atlas uplift set the area present structure (Monbaron 1981, 1982).

The Beni Mellal Atlas is set at the contact of the Middle and High Atlas, tectonically marked by the Afourer - Aghbala thrust fault (Monbaron 1981). A complex imbricate structure of faults and thrusts roughly oriented NW-SE defines the Beni Mellal anticline (Bouachou 1997, El Khalki et al. 2005, Figure 3.4). The massif's lithology is mostly formed of massive Early Jurassic limestones related to a platform domain, excepting the southern part formed of Middle Jurassic marls deposited in a deeper sedimentation bassin (Beni Mellal geologic map, 1:100'000, Figure 3.3). On the Tadla plain contact, the Atlas Early Jurassic formations caught Tertiary sediments in folding thrusts, forming the piedmont or *dir* formations (Bahzad 1982, Monbaron 1982, Figure 3.4). These are mostly formed of sandstones, freshwater limestones and sulphate limestone (Beni Mellal geologic map, 1:100'000, Figure 3.3). The Tadla plain itself consists of a rift delimiting the High Atlas and the palaeozoic Central Meseta and is filled with Miocene and Quaternary sediments (Bouchaou 1997).

The Beni Mellal urban perimeter is set at the outlet of four highly torrential catchments of relatively small surface. Relief is important, as altitude spans by 1500 to 1800 meters between the highest points and catchment outlets. Some of the catchment surfaces are set on marls inducing fast runoff, with sparse vegetation increasing this effect. The imbricate fault structure impacts the catchment morphology in that steep gorges and larger valley bottoms alternate accordingly. The *dir* belt marks the last narrowing of the valleys before the fan apex. In the Sabek, Ain el Ghazi and Handak catchments, these formations are integral with the Atlas formations; in the Kikou catchment the piedmont belt individualises, forcing the stream to skirt it in order to attain the Tadla plain. Large alluvial fans performed geomorphic adjustment between the high-energy highlands and the Tadla plain during Late Tertiary and the Quaternary (Beni Mellal Geologic map, Figure 3.3). Nowadays fossil, the fans are partly crust-topped due to the high carbonaceous content of their forming material.

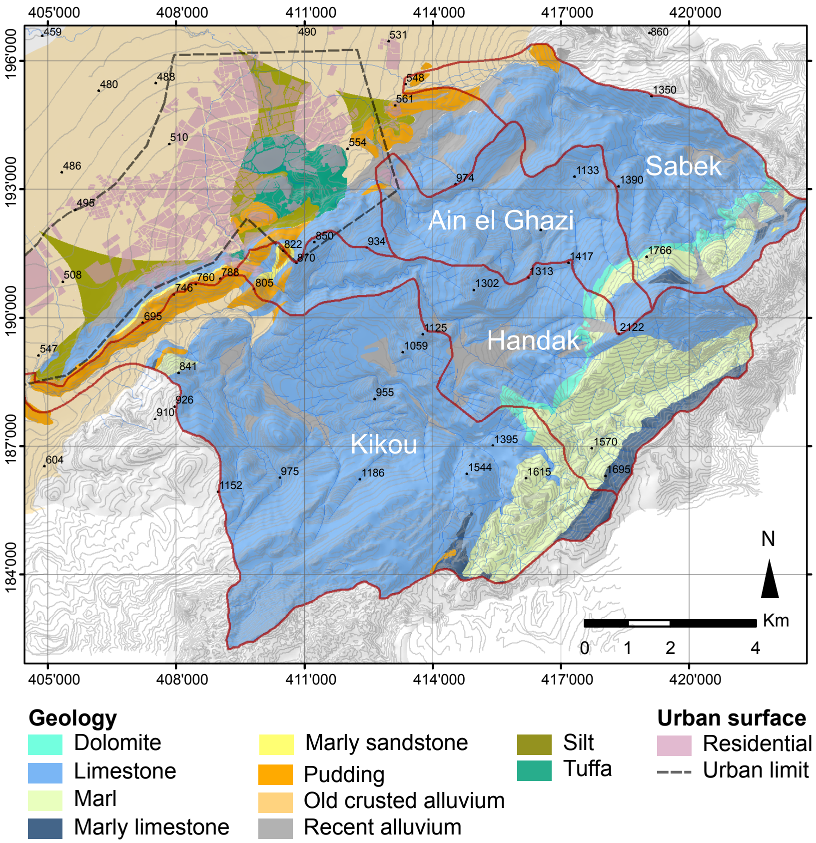


Figure 3.3. Study area lithology. From Monbaron M.: Beni Mellal geologic map, 1:100'000.

The massive Early Jurassic limestone series allowed the development of a series of karstic structures, formed by surface landforms such as lapiés and sinks, and a well-developed underground network converging towards several important karstic springs at the *dir* limit (Bouachou 1997, El Khalki & Hafid 2002). An important Early Jurassic aquifer, supplied by an underground catchment significantly larger than the topographic one, is linked to the Tadla plain aquifer through the folded *dir* series (Bouachou 1997). The four catchments in this study supply the Aïn Asserdoun exurgence, set at the *dir* base, that represents the main drinking water source in Beni Mellal (El Khalki & Hafid 2002). The good water quality results of a long filtration period 70 – 80 days) in a rather complex karstic aquifer (Bouachou 1997). However, during intense rainfall events, the spring presents strong turbidity reflecting important climatic and anthropic impacts on the catchments (El Khalki & Hafid 2002). The response time of the Aïn Asserdoun spring, as reflected by the turbidity change, is of 24 – 72 hours (El Khalki & Hafid 2002). The mean inter-annual discharge is of 1.1m^3/s; the spring supplies an important traditional irrigation system of *seguias* that supports the intensive olive culture on the *dir* and alluvial fan slopes.

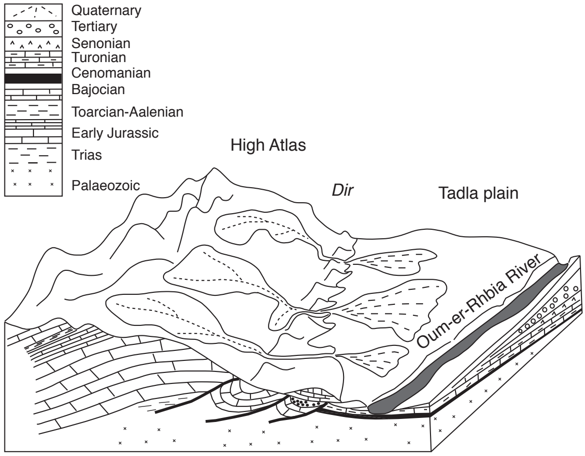


Figure 3.4. Block-diagram showing the stratigraphy, structure and relationship between the High Atlas, *dir* and Tadla plain domains. Modified from Bouchaou (1997).

The existence of a karstic system in the Beni Mellal Atlas had important consequences in terms of socio-economic development, as the *dir* springs have a perennial regime that compensates for the summer drought (Loup 1960) allowing agriculture to develop.

3.3.1. Sabek

The Sabek catchment is bounded at the SSE by the Tasmit-Iloughmane summit ridge with altitudes ranging from 2000 to 2200m (Figure 3.5). Progressing northwards altitudes decline as do the limit with the Taghaghat (ENE) and Handak (SW) catchments. The outlet is situated to the N in the Hadouz village (650m), at the apex of a large crust-topped alluvial fan. The Sabek stream bypasses it incising a gorge-like valley at the contact of the alluvial fan with molassic *dir* formations. Early Jurassic limestones dominate the catchment lithology except for the Tasmit summit ridge formed of marls and marly limestones outcrops. Vegetation is sparse, mostly formed of degraded *matorral* (typical Mediterranean secondary vegetation formed of xeric shrubs), patchy oak forests and non-irrigated crop fields (*bour)*.

Poor vegetation cover, high relief energy and the availability of friable outcrops may explain this catchment's highly torrential behaviour. High energy flows and massive bed load transport could be recorded at the catchment outlet in the Hadouz village. Further on, cobble-size bed load transport and deposition could be traced at the surface of the old quaternary fan (Photo 3-1). Floods reach in water sheets the lower city neighbourhoods to the confluence area with the Day stream. The Sabek and Aïn el Ghazi stream channels disappear short after passing the alluvial fan apex: thereafter storm water is evacuated by sheet flooding. Water sheets are then directed by topography to the lower confluence point where they meet Handak and Day streams. In order to mitigate flood related risks, local authorities plan to recreate stream channels by excavation and deviate streams towards a junction point situated northern of the present Day confluence area.

3.3.2. Aïn el Ghazi

The smallest studied catchment (Figure 3.6, Photo 3-1) is delimited southern by the Tasmit summit ridge (2200m); to the ENE and the SW it shares boundaries with the Sabek and Handak catchments respectively. To the N, its outlet is set in the village of Aïn el Ghazi, at the contact with the *dir.* Lithology is marked by Early Jurassic limestones that induced a lower landform fragmentation as well as the incision of deep valleys. Vegetation is homogenous, mostly formed of oak forests and *matorral.* The access to a limestone quarry and the building of a flood-reduction dam in 2010 required tracing a road to the village of Aïn el Ghazi. Set in colluvium-covered slopes, the access facilities have led to slope instability and sediment mobilization, therefore increasing the potential for bed load production.

After incising a 1km-long gorge-like valley in conglomerates of the *dir,* the Aïn el Ghazi stream ends its trajectory on a fossil alluvial fan where channel strongly narrows before disappearing in a renewed small-scale alluvial fan at the limit with the Tadla lowlands. Ain el Ghazi floods mainly concern the regional road Beni Mellal-Taghzirt, set at the fan apex and the national route to Fez where sheet floods of the Sabek and Aïn el Ghazi streams hinder traffic.

3.3.3. Handak

The Idemrane summit ridge (1900m) marks this catchment's SSE limit; elevations on the parting line between the Kikou (S) and the Aïn el Ghazi (N) catchments decline S-N (Figure 3.7). Its morphology is directly influenced by structure and lithology. Indeed, a series of orthogonal faults segments the valley in sectors so distinctive they bear different names (Loup 1960, El Khalki et al. 2005). The first, most southern sector called Bou Tout, set in marly friable outcrops, displays a gully-dominated morphology without vegetation cover (Photo 3-1). After a short gorge, the second sector is the relatively large valley bottom of Mouj set on Quaternary alluvium, with a village and olive plantations (Photo 3-1); a further gorge sector (Akka N'Khelila) rapidly transits flood waters to the catchment outlet where the stream bears the Handak name. At the gorges downstream end, a flood-reduction dam was built in 2009. The stream crosses the *dir* through an incised valley sector displaying two terrace levels at 30 and 5-15m.

On the alluvial fan, Handak stream kept a materialized streambed; it is probably due to residents' recurrent flood mitigation measures as old levee walls were still visible on the fluvial bed. The stream was modified in the context of the flood risk mitigation strategy local authorities adopted for the Beni Mellal urban perimeter. In July 2010, the stream channel was enlarged and deepened on the whole stream length crossing residential areas (5 km). Levee walls line the new channel stream. Stream junction with Day was also calibrated to a large confluence area surrounded by levees. Mitigation projects also include recalibration of the bridges crossing the stream. Presently, these induce a plug effect and consequent overflows.

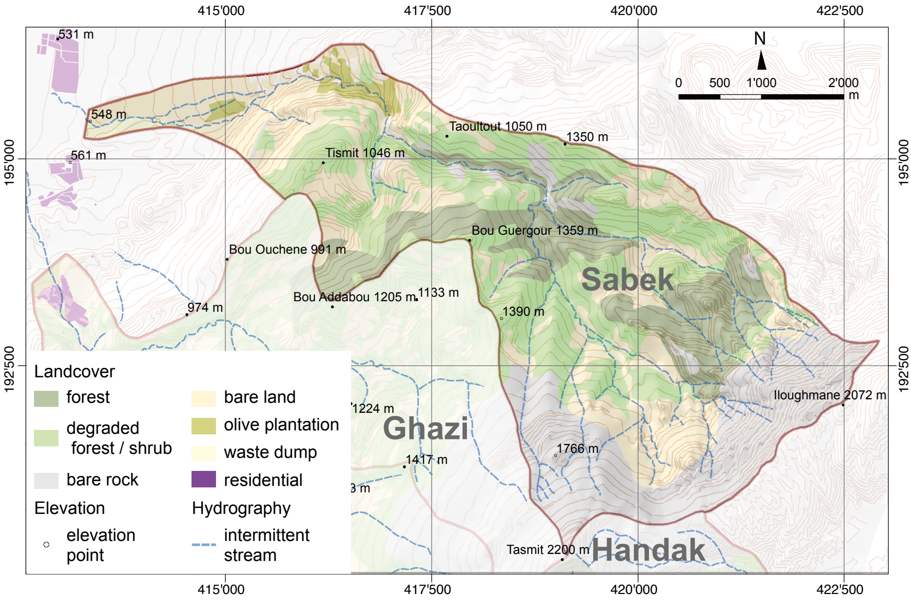


Figure 3.5. Sabek catchment.

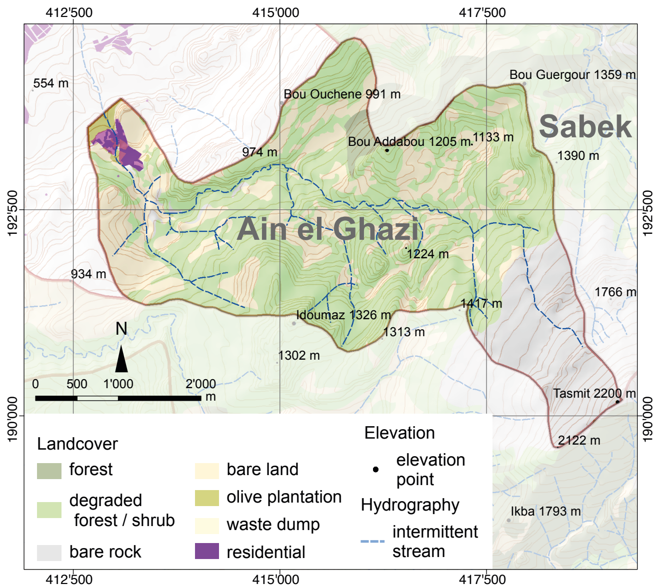


Figure 3.6. Aïn el Ghazi catchment.

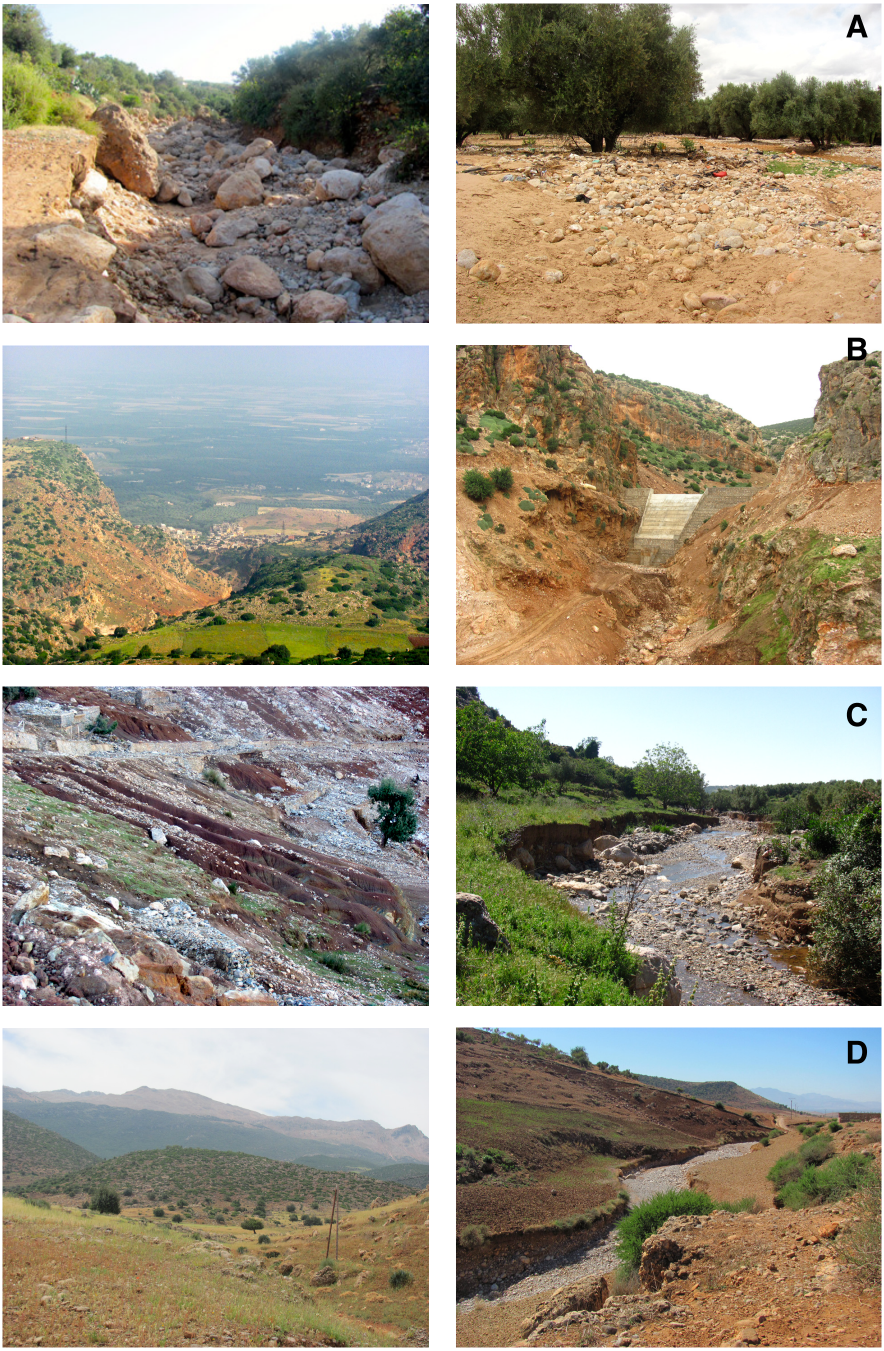


Photo 3-1. Views from the four catchments: a) Sabek; b) Aïn el Ghazi; c) Handak; d) Kikou.

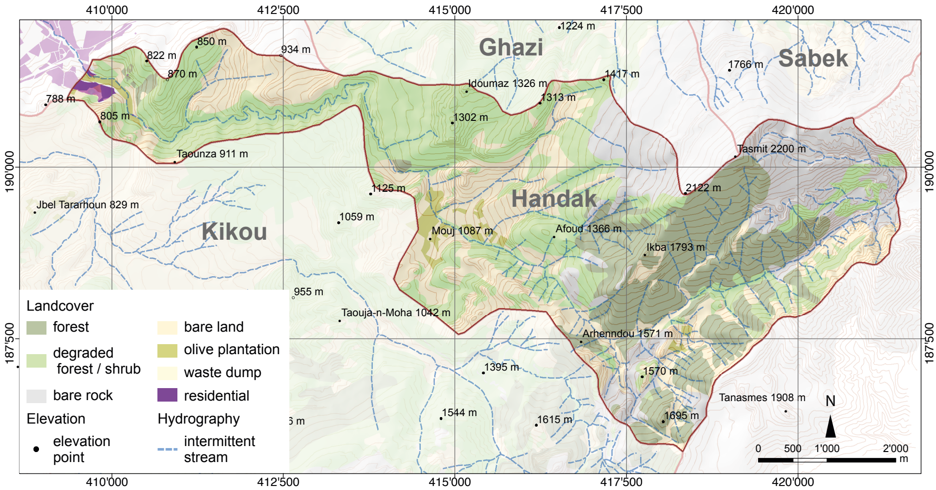


Figure 3.7. Handak catchment.

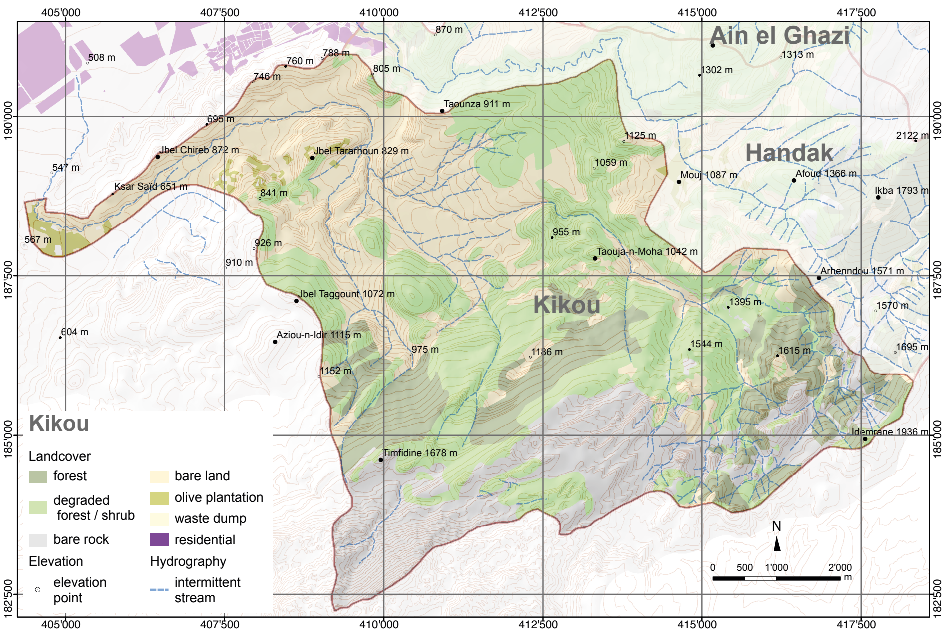


Figure 3.8. Kikou catchment.

3.3.4. Day

Day intermittent stream springs of a karst source situated at the base of piedmont tufa sequences; the source has dried out so that nowadays the stream drains mainly untreated sewage waters. Nevertheless, Day valley bottom forms the natural junction point of floodwaters that it drains, through relatively well-defined alluvial bed and floodplain out in the Tadla lowlands to the junction with the Oum-er-Rhbia River. The mitigation measures planned for this stream include channel enlargement downstream of the junction point up to the urban perimeter boundaries.

3.3.5. Kikou

The Idemrane summit ridge (1900m) set on friable marls and marly limestones marks the southern limit of the largest catchment in the study area (Figure 3.8). To the S-SW the catchment limit it borders a karst plateau with no surface flow, while to the SE it follows the Handak separation line. To the W, a hilly ridge relying Timifdine (1678m) to Jbel Taggount (1072) marks the catchment limit, while to the N Kikou stream flows E-W along the *dir* before switching SE-NW and incising a fossil alluvial fan. Early Jurassic limestones dominate lithology except for the SW part (Idemrane) where marls outcrop.

Relief energy is lower than in the other catchments; karst plateaus in the S display no vegetation while the middle Kikou is covered with *bour* crop fields that remain bare between crop seasons (Photo 3-1). Land cover conditions result in great runoff potential during the dry season, exposing this catchment to important floods due to typical convective storms.

The Kikou stream incised the old Quaternary alluvial fan up to the Fez-Marrakech national route. During winter, overflow floods occur on the fan when bed section capacity is exceeded. In the fan distal area, when crossing the main road linking Marrakech to Fez, the stream channel disappears. A sewage channel then drains flows: during floods, water overspills on the regional road leading to Fkih Ben Salah. A large irrigation channel perpendicularly crosses the existing draining structure. Large floods in 2009 induced here an overspill of the irrigation channel damaging unregulated housing dwellings situated nearby. The local authorities planned a recalibration of the drainage facility. Yet, the drainage problem subsists at the irrigation channel crossing where the drainage channel should be excavated deep under the irrigation channel level.

3.4. Hydro-climatic context

Climate change scenarios predict more intense and frequent thunderstorms North of the Atlas, as well as a concentration of the winter rainfall period (MATUHE 2001b). In this context, flash flood recurrence is likely to increase in the studied area, particularly as their runoff potential is thought to have increased during the last decades (El Khalki & Benyoucef 2005, El Khalki et al. 2005).

The studied region is part of the Mediterranean hydro-climatic region defined by seasonal contrast between mild, relatively wet winters and dry and hot summers (Hooke 2005, Figure 3.9). The region is under the influence of an eastward general atmospheric circulation related to cyclones developing during fall and winter in the North Atlantic (Lionello et al. 2012). Orographic effects play a fundamental role in moisture capture and consequent rainfall production. During summer, the Azores high-pressure zone hinders precipitation formation. The role of topography is noticeable in the annual precipitation difference between the more arid Tadla plain climate (425 mm/year at Beni Mellal, elevation 400 m) and the sub-humid mountainous area (679 mm/year El Ksiba, 1500m altitude) (El Khalki et al. 2005, Werren et al. 2013). Indeed, orogeny effects may be very localized in this area, producing intensive convection rainfall events at a very small scale inside the catchments. Therefore, flash-flood alert is difficult at the basins' outlet in the urban area.

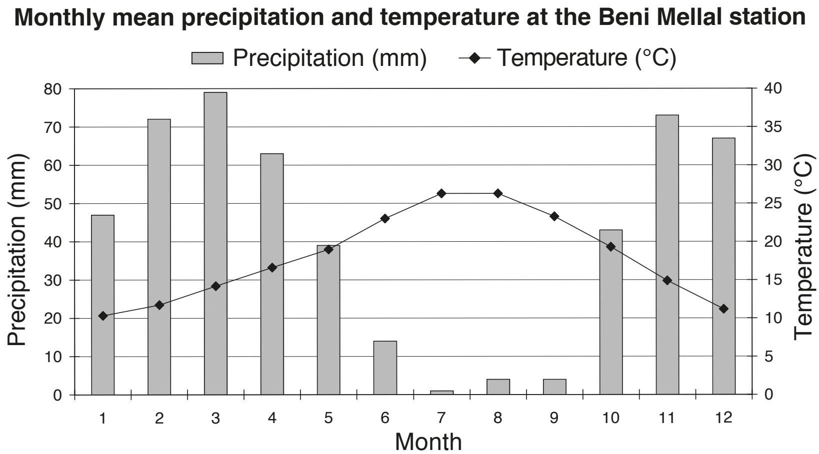


Figure 3.9. Beni Mellal station climograph. Source: Maroc Météo.

The Mediterranean precipitation regime is two-season; nevertheless, its most defining aspect is variability, be it inter-annual or intra-annual. This impedes climatic trend derivation from often scarce and inhomogeneous climatic data. Figure 3.10 displays annual rainfall at the Beni Mellal rain gauge. One can notice a slightly increasing trend in the past 15 years, dominated by inter-annual variability.

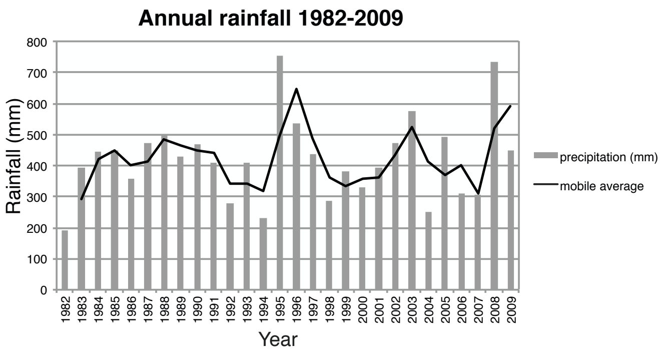


Figure 3.10. Annual rainfall (mm) for the Beni Mellal gauge. Source: ABHOER

Climatic extremes related to Mediterranean variability are on the other hand very important in comprehending climate behaviour. That is, 60% of the seasonal precipitation amount may be credited to extreme precipitations (Lionello et al. 2012). Examining daily maximum rainfall for each month during the 1982-2009 period at the Beni Mellal rainfall gauge, one may notice that high intensity rainfall events are common except for mid-summer (Figure 3.11). These events, occurring in sparsely vegetated catchments are likely to produce fast torrential hydrologic responses in the shape of flash floods. Large floods occurred in Beni Mellal in 1995, when more than 700 mm precipitation was recorded (see Figure 3.10). According to rainfall characteristics and intensity, and to catchment response, these were flash floods turned into sheet-flood inundations on the gently sloping alluvial fans and the urban area built thereupon. Urban infrastructures like bridges and the street net play a major role in flood overspills and channelization.

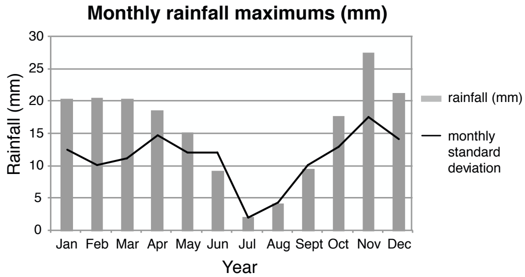


Figure 3.11. Daily rainfall maximum (mm) for each month during the 1982-2009 period at the Beni Mellal rainfall gauge. Source: ABHOER.

Increasing temperature extremes over the past decades match the global warming trend; nevertheless, in North Africa this trend is higher. Indeed, the Moroccan climate zones have been re-classified to respond to this forcing (Zeino-Mahmalat & Bennis 2012). In the past, droughts have been found to increase wildfire occurrence in the western Mediterranean, influencing vegetation patterns. Even though they are climate-related, 95% of wildfires are of human origin (Luterbacher et al. 2012): this emphasizes the importance of human impact on the Mediterranean environment to the point that "it may obscure climatic signal" (Luterbacher et al. 2012).

Climatic and hydro-meteorological data available for the concerned area can be defined as scarce. Indeed, the Oum-er-Rhbia Catchment Agency owns several daily rainfall gauges within this mountainous area, set at distances of 20 – 50km away from the studied catchments. The Beni Mellal meteorological station, part of the National Weather Forecast Agency, reports other hydro-climatic parameters (e.g. hourly temperature, rainfall, radiation data). Nevertheless, these data are not representative of the upland catchment conditions, as elevation span between catchments highest points and Beni Mellal can attain 1500m. Finally, radar rainfall records were produced within this area since 1998, but the National Forecast Agency does not provide this data.

The flood history in the city of Beni Mellal is short. Indeed, local authorities first acknowledged flood problems in 1995, followed by repeated events in 1996, 2001, 2002, 2003, 2008, 2009, 2010, as reported by El Khalki & Benyoucef (2005) and different internal reports handed by the Wilaya. According to the Catchment Agency, most of the flood overflows were triggered by inadequate infrastructure and the important decrease in cross-section capacity of the streams that cross the city of Beni Mellal (ABHOER 2004).

3.5. Human impacts and vulnerabilities

Humans influenced Mediterranean ecosystems to an extent never attained in other morpho-climatic regions. At the same time, people are vulnerable to natural or human-induced hazards in a region with increasing aridity and more recurrent hydro-meteorological events. What are the human-related impacts and vulnerabilities in the study area?

First, the city of Beni Mellal developed thanks to the important water resources provided by a series of karstic exurgence springs located along the *dir,* that were supporting a perennial regime in the streams that cross the city. Irrigation guaranteed the development of extensive olive plantations that mark the Beni Mellal cultural landscape, but water withdrawal during the dry summer months had an impact on the streams natural regime. Indeed, the streams discharge became dependent on winter precipitation and spring snowmelt.

At the catchment level, humans left their imprint on the natural ecosystems by logging, fire clearance and slope structuring with terraced crop-fields. These influences date in the Mediterranean from the Bronze Age (Luterbacher et al. 2012), its main marker being the development of the secondary forest – shrub land vegetation cover called *matorral* in the studied region. Traces of the recurrent deforestation and wildfires are visible in the gharbian (Holocene) fluvial terrace of the Handak stream at Mouj where alternating grain-size distributions and charcoal levels display cycles of erosion and system adaptation (El Khalki & Benyoucef 2005).

Some deforestation effects may be contemporary, as El Khalki & Benyoucef (2005) point out with geomorphological evidence of recent soil removal on surface karst forms (lapiés) in the Handak catchment. Since 1970, the region was subject to drought that set increasing pressure on pastureland and forest. At some extent, cropland areas enlarged in order to respond to the needs of local populations. Indeed, the traditional non-irrigated cultures *bour* depend solely on precipitations; therefore larger fields would increase crops chances if rainfall permitted. Drought, causing massive rural migration, brought also the contrary effect: cropland abandonment, deteriorating terraced slopes, and local economy reorientation towards the city via the charcoal commerce that implied more deforestation. These changes in land cover have substantially influenced catchment hydrologic response since 1995 when the precipitation pattern changed. Resulting floods became a problem in the downstream fast-urbanizing area of Beni Mellal.

Indeed, during the drought period, the city and lowlands of the Tadla plain became more attractive for the mountain rural populations after the building of several retention dams (Kasbat Zidania in 1930, Bin el Ouidane in 1950), and the setting of large irrigated perimeters in the plain (Beni Moussa, Beni Amir). Economic attractiveness and the effects of drought on the mountain agro-pastoral activities set massive rural exodus towards the capital city of the Beni Mellal province (El Khalki et al. 2005). Population and unregulated housing have boomed in the city since 1980 (Figure 3.12), at the peak of the drought effects. The construction pace continues to be high nowadays, stimulated by external remittances from international immigrants (Figure

3.13). El Khalki et al. (2005) point out the role in heritage loss that land speculation and urban sprawl play inside the agricultural areas of the Tadla plain and the traditional olive plantations of the *dir.*

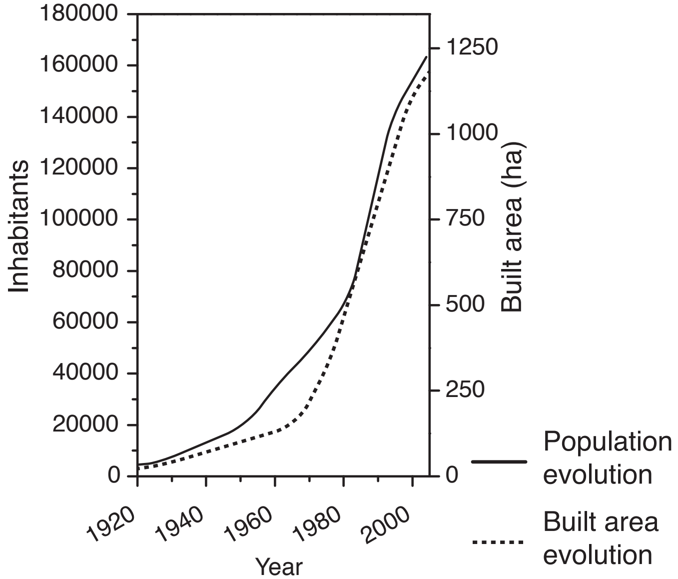


Figure 3.12. Population and built surface evolution between 1920 and 2005. Source: El Khalki et al. 2005.

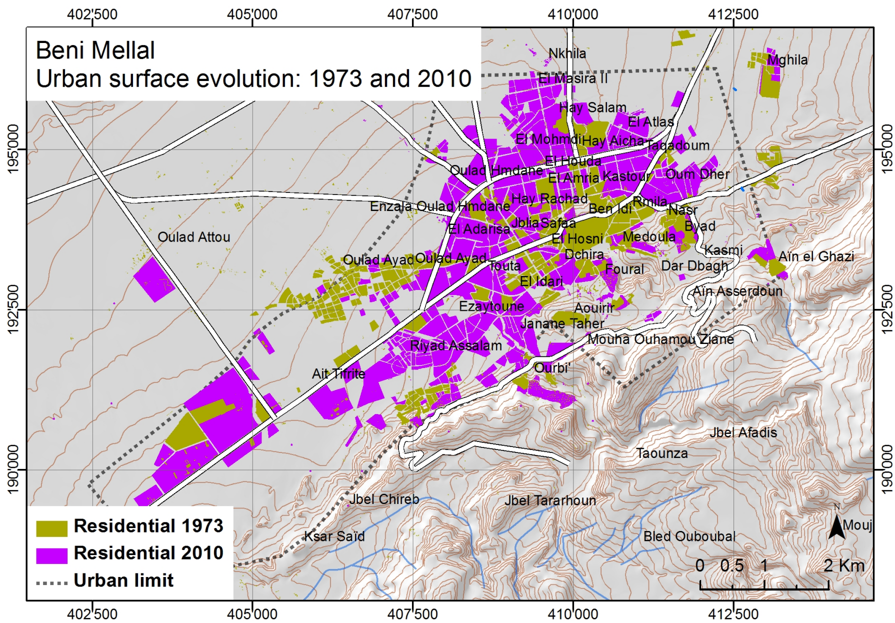


Figure 3.13. Urban sprawl in Beni Mellal between 1973 and 2010.

Urban sprawl on the inundation areas of the four alluvial fans and the low confluence point at the north of the city increases dramatically flood vulnerability. Low quality housing, inadequate urban infrastructure and the difficulty authorities face in regulating constructions represent more vulnerability triggers. In this context, hazard assessment and mapping may inform about vulnerability and represent an important tool in urban planning and regulation.

3.5.1. Implications for the methodological approach

People’s exposure to flood hazards has increased over the past decades in the city of Beni Mellal. In this context, it is appropriate to expect that by assessing and mapping flood hazard, and by orienting further planning relative to flood hazards, a decrease in exposure will occur, and thus risks related to flooding will decrease. Nevertheless, flood hazard assessment needs to account for the environmental and human specificities of the study area.

Indeed, the four catchments responsible with flood hazards in the city of Beni Mellal are ungauged, and prone to develop flash floods. Their hydrological behaviour is regulated by the highly variable Mediterranean climate, precipitous topography and limestone – marl lithology with high potential runoff, especially in degrading vegetation conditions. Thus, a through knowledge of the physical conditions in these catchments, as well as understanding the hydrological processes likely to occur are essential conditions for realistically assessing hazards. Moreover, the lack of measured data, require on one hand seeking for alternative data sources, and on the other hand using field knowledge in order to compensate for data scarcity. Finally, flood development within the urban area of Beni Mellal is in direct relationship with the peculiar alluvial fan morphology, prone to sheet flooding and uncertain flow path development. Here too, using field knowledge is essential for realistically predicting flood development and for further hazard assessment.

4. Hydro-geomorphic mapping

In this chapter we discuss the adaptation of Swiss hazard-related geomorphic maps to the realities of a semi-arid urban environment in a developing country like Morocco. We focus on floods that represent the main hazardous process on our study site. We first present the Swiss geomorphic cartography method and the necessary adaptations to a different environment illustrated by specific mapping methodologies. An adapted synthetic approach to mapping is then used to produce a flood hazard-related geomorphic map whose conclusions are discussed in terms of results, method applicability and place in the hazard mapping process.

4.1. Geomorphic maps in the Swiss hazard mapping process

Natural hazard mitigation is a three-stage process consisting of hazard identification, hazard assessment and mitigation measures planning (Loat & Petrascheck 1997, ARE, OFEG, OFEFP 2005).

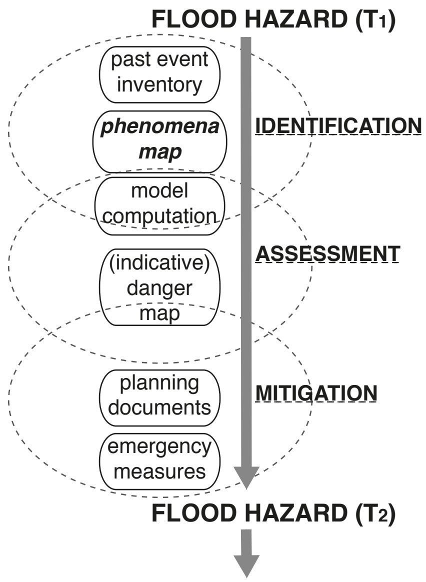


Figure 4.1. Geomorphic maps in flood hazard management context. T1, T2: time variables. Modified from Kienholz & Krummenacher (1995).

Phenomena maps containing hazard-related geomorphic and anthropic elements are technical documents related to the first stage, their objective being to acknowledge hazard in the field by mapping hazard-prone critical areas and the geomorphic markers of past events (Kienholz & Krummenacher 1995). As shown in Figure 4.1, mapping *phenomena* may encompass approaches related to the second stage. Indeed, by mapping process intensity, these maps partially assess natural hazards.

4.1.1. The importance of *phenomena* maps

Phenomena maps provide spatial representations of hazardous natural phenomena. By mapping markers of past phenomena, these geomorphic maps state that past is likely to inform us about future manifestations of a given phenomenon. In the case of cyclical phenomena like floods, geomorphic indicators of extreme past events are fundamental for understanding the **system behaviour**, phenomenon extent and probable intensity, particularly in areas untouched by active mitigation measures.

Critical areas represent hazardous geomorphic conditions (e.g. insufficient river curvature radius that may result in flood overspills) or inappropriate infrastructure (e.g. flow restricting bridge sections). Mapping these elements allows a broader understanding of natural conditions on one side, and of **human interactions** with the natural system on the other side (Loat & Petrascheck 1997).

Hazard assessment for Swiss hazard map design is based on the findings of different complementary documents such as past event inventories, geomorphic maps and models of expected system behaviour. Information contained in these documents is used for final hazard assessment. Therefore, *phenomena* maps inform and sustain **decision-making** in the process of hazard map conception.

Finally, *phenomena* maps provide graphical representations of hazardous phenomena directly related to reality. They are likely to be communicated and allow end users of hazard maps to comprehend the leading criteria in the choice of hazard classes. Indeed, phenomena maps are used in the hazard mapping procedure as a justification means for the other assessment methods. From this point of view, geomorphic maps related to hazard map conception justify and bring **transparency** to the hazard assessment process.

4.1.2. Method description

In Switzerland, geomorphic maps related to natural hazards have been produced since 1930, following specific methodologies for each hazard type or the needs of particular studies. The 1991 Forest Law (*Loi fédérale sur les forêts*, LFo, 4.10.1991, RS 921.0) which stipulates cantons' and municipalities' obligation to design maps for a set of natural hazards, created the legal framework necessary to the outline of an homogeneous methodology for hazard mapping via federal guidelines. *Phenomena* mapping guidelines have also been produced (Kienholz & Krummenacher 1995) in order to synchronize hazard identification process at a national scale.

The *Swiss adaptable phenomena map legend* (Kienholz & Krummenacher 1995) ensures this synchronization. It may be considered as **homogeneous** since it was designed for mapping all natural hazards stipulated by the Lfo (floods, avalanches, debris flows, rockfalls, landslides), be it separately or synoptically. By using one colour per specific process, the adaptable legend enhances map legibility when drawing several geomorphic processes at a same location. Guidelines stipulate also considering process hierarchy and the emphasis of dominant processes.

Moreover, this legend is **scale-flexible** and **adaptable** as it can be used for designing regional hazard-related geomorphic maps or more detailed maps for the municipal planning documents. Two scale-related legends have been proposed to map designers. The general legend, adapted for 1:25’000 to 1:50’000 maps, consists mainly of surface relevant elements at the chosen scale. These maps form the basis for cantonal indicative hazard maps necessary to cantonal planning (*Plan directeur cantonal*). A more detailed legend suitable for 1:2’000 to 1:10’000 maps is embedded in the general legend. It consists of surface and punctual elements describing in detail geomorphic processes, their origins and possible future behaviour (Appendix 2). These maps represent basic documents for detailed hazard maps design used for the municipal Zoning Plan (*Plan d’affectation des zones).*

Swiss geomorphic maps depict processes in a **dynamic** way in that they graduate process intensity, depth, age, and activity using colour and symbol gradients. Likely, elements’ apparent or supposed character is outlined through symbol graduation. To some degree, maps represent an event’s possible intensity, and offer a good insight on hazard spatial distribution and weight. In some cases, they might represent the main input for subsequent hazard maps. Nevertheless, the Swiss hazard mapping methodology does not only use geomorphic maps: computational model methodologies, even though less regulated, represent an important prediction tool widely used by map designers.

In conclusion, geomorphic or phenomena maps are likely to point out those areas where active processes occur (e.g. riverbank erosion, active sediment accumulation on an alluvial fan) and so to provide insights on the possible location and intensity of the hazardous phenomena. They also represent so-called critical areas for flood development, often related to river – human interactions and thus provide a better understanding of the influenced hydrological behaviour. Finally, geomorphic markers of past events provide an initial estimate of the spatial extent further events may attain. Nevertheless, geomorphic maps are not likely to provide precise magnitude estimates, especially in the case of floods; thus, hazard assessment also requires modelling approaches.

4.2. Method adaptations

The Swiss hazard mapping methodology offers a comprehensive, homogeneous framework for designing maps that draw conclusions based on multiple data sources and methods. It has proved its ability to respond to diverse needs in a consistent manner at the national scale through unique guidelines and case adaptation possibilities (Kunz & Hurni 2008).

However, to use this method for flood hazard mapping in completely different natural environments like the Mediterranean study site in Morocco, one must foresee particular adaptations. Indeed, semi-arid hydro-climatic regions embed different climate-induced hydro-geomorphic dynamics and at some extent different morphologies. On the other side, one must take into account the specific urban character of our study site where geomorphology may be masked or modified by human activities.

4.2.1. Climatic, morphologic and urban constraints

Among all hazards, floods require a very particular treatment since they are climate-dependent. Mediterranean hydro-climatic regions display specific hydrologic dynamics based on contrasting seasons that influence at some extent the morphology. Likewise in these mountainous regions measured hydro-meteorological data is fairly scarce impeding good statistical knowledge of hydrologic responses. Therefore, good knowledge of hazard-related geomorphology is essential to flood hazard mitigation and is likely to compensate or replace model calculations of hydrological responses.

Photo 4-1, Active fan transport and deposition zones of (a) Sabek and (b) Aïn el Ghazi streams.

Large alluvial fans are common in mountain - plain contact areas of semi-arid and arid regions with important sediment yields (Bull 1977, Coque 1998). This specific morphology impacts directly flooding characteristics and hydro-geomorphic dynamics inducing fast water dynamics, sheet-flooding and unpredictable flood paths and sedimentation. Alluvial fans present braided flow patterns where channels alternate with alluvial bars (Photo 4-1a); active fans formed of mobile sediments are subject to rapid structure changes and avulsion phenomena (channel abandonment by levee breach and abrupt channel direction change) (Bull 1977, Blair & McPherson 1994). In distal areas, flooding turns to sheet patterns (Photo 4-1b).

Photo 4-2. Infrastructures of inappropriate dimensions can radically influence flood behaviour. Here exacerbated erosion downstream of the Marrakech road on Kikou stream in 2010.

Alluvial fans tend to stability in two ways (NRC 1996). First, in catchments with high capacity, channels may incise the fan surface to a point where the braided pattern becomes one-channel. This situation is inherited on the apex section on the Sabek stream that incised a channel at the fan contact to the *dir.* In catchments with stable sediment balance, channels may narrow down towards the distal areas where sheet flooding dominates. Small-scale channel structure changes may occur here. The alluvial fans of our study site belong to this type of stabilized fans. In terms of flood hazard, alluvial fans differ from classical alluvial plains in that there is no deterministic relationship between morphologic channel limits and flood frequency. Flood paths are difficult to predict, water inundation may occur with sedimentation, and avulsion risk amplifies unpredictability.

Riverine lowlands and gently sloping alluvial fans have become valuable urban development sites due to their accessibility (Schick et al. 1999). Thus urban surfaces tend to mask or diminish the morphologic markers of rivers' hydro-geomorphic behaviour making it difficult to map them. On the other hand, the cohabitation of people and rivers has been marked by systematic changes in the streams' natural structure by means of protection levees, longitudinal profile transformations and the effect of bridges (Photo 4-2). This situation is well represented on our study site. It is therefore essential to account for the role of urban structures in flood event development.

4.2.2. Available methods outlook

In order to respond to climatic, geomorphic and urban constraints specific to an environment so different as the semi-arid Moroccan one, the Swiss geomorphic mapping method needs to be adapted. Several hazard-mapping methodologies based on geomorphic mapping have been developed to respond to some of these specific constraints. Some of these methods tend to prefer geomorphic mapping to any other hazard assessment approaches, e.g. hydrologic or hydraulic models. This is justified by the generalized lack of data availability in the regions where these methods have been developed. For this study we retain the geomorphic mapping elements these methods propose as a part of hazard identification and a means to justify hazard assessment, in the context of the Swiss hazard mapping methodology.

Hazard assessment in semi-arid regions

The Hydrogeomorphic method, developed for Mediterranean streams in the South of France, is based on the assertion that alluvial plains are structured by extreme flood events (Masson et al. 1996, Ballais et al. 2005, Ballais et al. 2011). In cyclic systems like fluvial environments, one can expect that present flood extents correspond to past ones; this method states that alluvial plains conserve several limits of past floods: the mean water channel, the intermediate flow channel, and the floodplain (Chave 2002, Ballais et al. 2005, Figure 4.2).

This method analyses therefore alluvial plain components and their limits in order to ascertain their specific flood hazard frequency and relative magnitude (see Table 4.1). Corresponding hazard magnitude may however be influenced by inappropriate hydraulic structures hindering flood propagation. Alluvial plain mapping is undertaken via aerial image analysis and field campaigns. Cost-effective, this naturalist method is widely used in France for flood risk assessment (Ballais et al. 2005, DIREN-PACA 2007). It does not allow nevertheless prediction of flood intensity (Chave & Ballais 2006). The alluvial fan morphology present in our field site makes this method inappropriate for a large part of it; we retain though the idea that certain morphologic limits may be related to specific flood frequency and hazard magnitude. It is, however, more suitable for the alluvial plains present on our companion study site in Fez (Lasri 2013), where it is likely to resolve urban masking effects at the floodplain level.

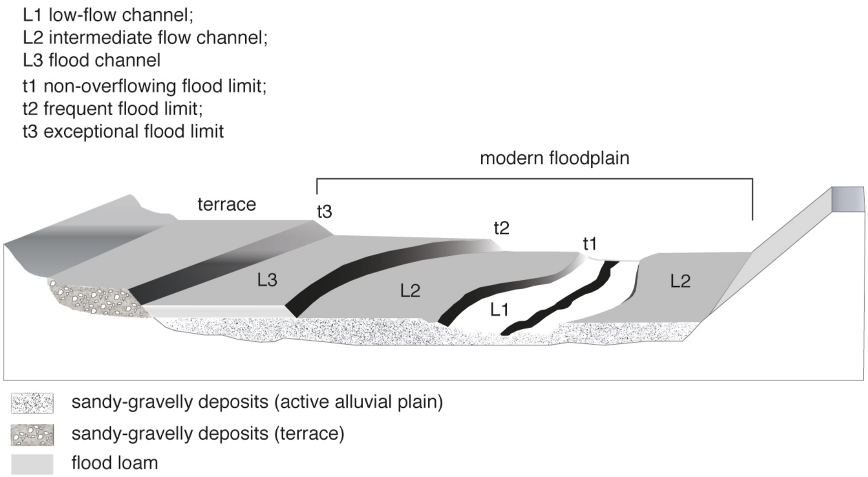


Figure 4.2. Floodplain morphology relationship to flood frequency. From Ballais et al. (2005).

Alluvial plain component	Flood return period	Hazard magnitude
Mean water channel	1-2 year	
Medium water channel	2-10 year	High to very high hazard
Flood plain	10-100 year	High in secondary channels, medium in flood plain
Exceptional flood plain	> 100 year	Low
Terrace	No flood	No hazard

Table 4.1. Alluvial plain components and their hazard significance. From DIREN-PACA (2007)

In Spain, a risk-oriented method developed for Mediterranean ephemeral streams (Camarasa-Belmonte & Soriano-Garcia 2008, 2012) bases hazard assessment in a qualitative way on geomorphic mapping. That is, geomorphic forms present in a floodplain are given a qualitative hazard degree subsequently crossed with equally qualitative vulnerability degrees in order to obtain dynamic risk maps strongly influenced by the assets' effective vulnerability (night / day occupation, institutional / residential use). This method is useful in regional scale studies of hazard-prone areas identification. In this study's context however, this method finds poor applicability.

Monitoring reference events

Monitoring important reference floods from a hydro-geomorphologists' point of view is likely to compensate the inherent lack of measured data in semi-arid regions but also in other developing countries. The *Integrated Geomorphic Method* (Fernandez-Lavado et al. 2007, Furdada et al. 2008), developed on this principle, has been applied in very different hydro-climatic and morphologic environments: Nicaragua (Furdada et al. 2008), San Salvador (Fernandez-Lavado et al. 2007), or Morocco (Taous et al. 2010).

This integrative approach tends to take into account all flood-related available sources of information for a given area (maps, hydrologic data, archives and field-collected inventories and testimonies) in order to assess flood hazard. In the absence of information related to flood frequency, a rare, reference event is studied in detail using field and remote sensing methods able to determine flood extent (Photo 4-3a, b), water levels (Photo 4-4) and velocity estimations from geomorphic "silent witnesses" and community-based flood event knowledge.

Photo 4-3. Flood extent mapping as a means for hazard assessment verifications. Blue line: latest flood limit.

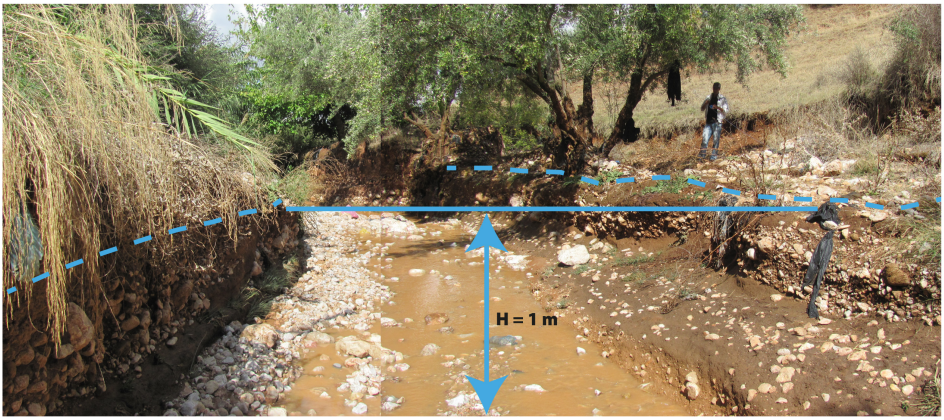


Photo 4-4. Wetted section estimates provide means for hazard assessment verifications.

This method proposes a large panel of approaches likely to assess correctly and to predict flood hazard subsequently in regions where natural or social factors impede sufficient data availability. The geomorphic approach was developed to compensate and at the same time verify the results of other prediction methods (e.g. hydrologic-hydraulic models). Its applicability is restricted to regions where sufficient rare events markers are available for assessment. Nevertheless, this approach is very useful in any conditions where a flood event could be monitored as verification means for other hazard assessment methods.

In a more hydrology-oriented approach, Gaume & Borga (2008) state that field-collected post-flood depth data from natural streams can compensate for the lack of measured hydrometric data by estimating peak discharges of a given flood event (Photo 4-4). This approach was specifically designed for flash floods, which have spatial and temporal development scales difficult to monitor with classical gauging. Withal, this method represents a hydrologic application of hydro-geomorphic principles.

Flood hazard assessment on alluvial fans

Alluvial fan morphology sets an important challenge for flood hazard assessment: on the one hand, computational models fail to predict phenomena like channel avulsion; on the other hand, there are no clear geomorphic delimitations similar to those in alluvial plains for assessing flood frequency.

The Federal Emergency Management Agency (FEMA), as the national manager of flood hazards in the USA, has assigned the National Research Council (NRC) the mission to deal with this challenge in a context of rapid urbanization of alluvial fans in arid and semi-arid regions of the country. In order to delineate the extent of the 100-year return period flood that forms the basis for all flood mitigation strategies in the United States, the NRC came up with a geomorphic-oriented flood hazard assessment methodology (NRC 1996) for alluvial fans. The method's basic idea is that flood hazard is not uniform on a fan surface.

This is a three-step methodology. First, alluvial fans must be distinguished from other geomorphic forms and their lateral and distal limits described. This step is very important in imbricated fan structures where limits may become vague. Then, erosion, deposition and inundation zones on the fan surface are identified as active. Younger, active fan parts are more likely to be flooded than older, inactive ones. Young / old demarcation is based on geomorphic criteria like sediment deposit age, channel network pattern and surficial morphology, alluvial fan surface erosion stage, and soil cover maturity. Inundation zones up to 1000 year are considered to be active fan parts. A final step consists in delineating the fan active parts that are subject to the 100-year flood (NRC 1996, FEMA 2000). The NRC methodology does not intent to replace model calculations; it provides instead sound geomorphic criteria for hazard-prone areas delineation on alluvial fans. It bids therefore confidence span and result verification means for hazard assessment.

4.2.3. This study's approach

This project has been shaped around the Swiss methodology for hazard assessment and mapping, in a double effort of knowledge transfer and adaptation to local realities in Morocco. Therefore, the Swiss *phenomena* mapping method and its elementary principles were preserved as a basis for our geomorphic approach to flood hazard. That is, our objective was to map all hydro-geomorphic and anthropic elements that play an active role in flood development and aggravation or explain hydro-geomorphic behaviours on the study site. The resulting *phenomena* map represents a hazard identification and assessment justification document.

Furthermore, monitoring contemporary flood events is central to understanding hydro-geomorphic behaviour in these ungauged catchments. Systematic flood extent mapping and water depth estimations from geomorphic markers provided us essential elements for further hydrologic and hydraulic model calculations. Mapping tools stipulated by the Geomorphic Integrated Method (Furdada et al. 2008) and hydraulic wetted section estimations (Gaume & Borga 2008) were integrated to the basic mapping process.

Alluvial plain delineation as developed by the French Hydrogeomorphic method was not likely to be used on the Beni Mellal alluvial fans; floodplain limits could be however determined for the downstream Day reach that channelizes floodwaters from the whole urban area. This method has been more intensively used on the Fez study field for floodplain delineation even though concentrated urbanization hindered detailed floodplain cartography (Lasri 2013).

Finally, we signal the important contribution of the alluvial fan-specific methodology developed by the NRC (1996) in the United States for the comprehension of current alluvial fan flooding dynamics. Indeed, flash floods produced in the upstream catchments invest these gently sloping surfaces where channels soon disappear; thus, flow turns into sheet flood. Active erosion and sedimentation areas, as well as visible flood extents were mapped using surface geomorphic markers.

The *phenomena* map takes also into account the role of different urban and hydraulic structures in the development of amplification of floods. The next section presents this study’s results in the form of the Beni Mellal geomorphic and anthropic flood hazard-related map.

4.3. Beni Mellal *phenomena* map

4.3.1. Mapping process

Geomorphic mapping is essential for flood hazard comprehension and assessment. We undertook this important stage in three subsequent steps.

A general cartographic and informative initial step allowed us to gather spatial information concerning the studied catchments and urban area. We therefore created a geographic database containing information about topography, geology, land cover, and hydrology. Large-scale urban plans obtained from local authorities provided detailed information at the city level and the base map for the cartography effort. Map extent was designated following several criteria: present and future urban surface extents as they appear in planning documents, or areas exterior to the urban spaces that influence flood development.

Then, a field stage consisted of actual mapping of all elements retained. Mobile mapping devices allowed us to gather spatial information at a very good detail level in relative low visibility field conditions (e.g. olive plantations). We focused on elements related to floods like:

- hydrogrological network elements and their characteristics;
- fluvial morphology and fluvial characteristics relevant for the studied watercourses dynamics;
- geomorphic markers specific for three different geomorphic "domains": valley bottoms, floodplains and large alluvial fans;
- inundation markers and residents' knowledge on flood extents for known flood events;
- anthropic elements that impact flows and their possible role during flooding.

A final cartographic stage consisted of integrating the mapped elements to the existing database. The map legend was structured according to field findings from two relatively different geomorphologic domains in Fez and Beni Mellal.

The base map, established on urban plans dating from 1999 in the case of Beni Mellal had to be updated to respond to the city's fast urbanization pace. Latest satellite images provided by GoogleMaps were used in this process. Map scale was settled to 1:15'000 for the city of Beni Mellal.

4.3.2. Mapped elements and hazard-related findings

Using the Swiss methodology for flood hazard-related *phenomena* mapping and adaptations to our study field, we inventoried hydro-geomorphic as well as anthropic elements that influence or describe flood development in the urban area of Beni Mellal. Two field campaigns were undertaken in 2009 and 2010. We hereby present the results of this study consisting of the Beni Mellal flood hazard related *phenomena* map. We signal that this work has been undertaken in close collaboration with the Fes-Saïs University LAGEA laboratory. Thus, its findings represent the compromise of a cartographic effort undertaken on two different morphologic domains: fluvial (Fez) and alluvial fan morphology (Beni Mellal).

Four element types have been distinguished: hydrological network, geomorphology, flood extents, and anthropic elements. Base map elements are important in phenomena spatial comprehension. Moreover, they form the base for hazard mapping through the land-use vulnerability information provided; they are hence described.

Hydrological network

Hydrological elements were designed by three categories of cartographic objects:

- hydrological network and flow typologies (permanent, seasonal, intermittent) were represented using linear elements;
- anthropic changes of the natural hydrological network (i.e. channels, deviations) were also represented. We equally represented traditional (*seguias*) and modern hydraulic irrigation systems that form secondary "hydrological"

networks that systematically influence flood development in the city of Beni Mellal;

- water bodies were represented with surface elements. This element is more suited for the Fez study site where lakes and wetlands occur (Figure 4.3);
- point elements design sources.

Only the seasonal and intermittent flow types are present on the study site (Figure 4.3): seasonal flow defines the four catchments that drain the city of Beni Mellal related to winter rains and snowmelt; intermittent flow is represented in several torrential basins (*châabat*) that drape the southern *dir* slopes dominating the city.

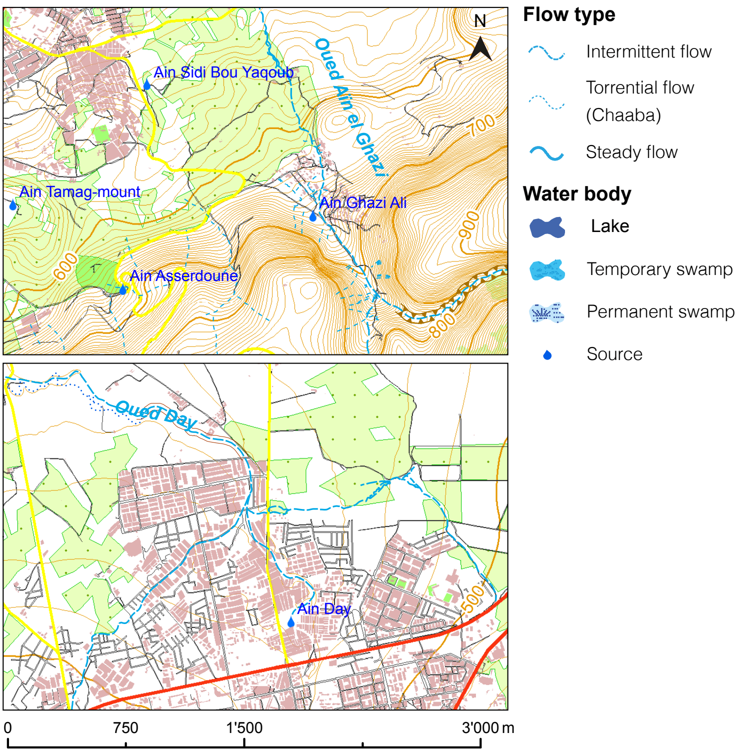


Figure 4.3. Hydrological network: mapping examples and legend.

In terms of flood hazard, seasonal flow implies long dry periods where slopes as well as valley bottoms are subject to desiccation phenomena. Material is “prepared” on slopes for transport during winter rainfall events, inducing important solid discharge at the catchment outlet. On the other hand, long dry periods specific of the 1970-1990 drought period induced important fine material channel filling on the alluvial fans. As a consequence, wetter years found these gentle slopes subject to sheet flooding colonized with residential spaces as flood risk memory had weakened during the dry years. Intermittent *chaabats* that overlook Beni Mellal participate to floods specially when generalized rainfall events touch the whole region. These brutal gushes touch the nearby recent settlements (Ayat, Ourir and Ourbi’) or enter the city’s street network that plays a flood-orientation role.

Anthropic alterations of the natural hydrography network are principally related to flood mitigation strategies. Their role in flood development is still difficult to assess as not all of the planned infrastructures were in place at the time of mapping. Therefore, one could reveal downstream flood aggravation related to unfinished channels and dikes. For example, dikes already built on the upper urban Handak reach resulted in generalized flood inundation in the downstream Al Massira district in September 2009. Stream deviation, planned for the Sabek and Aïn el Ghazi streams, is expected to cope with consequences related to high solid discharge in the newly built channels needing frequent dredging (Schick et al. 1999). Moreover, the artificial base level lowering of about 50m may induce geomorphic reactions of headward erosion.

Temporary water bodies form after important floods in the lower confluence area of Day stream (Figure 4.3). They are probably due to the rise of a shallow Tadla water table.

Traditional and modern irrigation channels (*seguias*) represent essential components of the Beni Mellal landscape and mark its agrarian profile (Figure 4.3). Traditional *seguias* that irrigate mainly olive plantations are alimented by karstic sources set at the base of the *dir*; therefore unlike the four streams that cross the city, their flow is relatively steady throughout the year. Often built along topographical depressions, this type of infrastructure orients and channelizes floodwaters during generalized rainfall events (Khalki & Benyoucef 2005). Moreover, the main karstic source of Aïn Asserdoun, set at the base of the southern *dir* has been witnessed to participate to the general flooding that took place in 2002.

Geomorphic elements

Actual geomorphic mapping challenged us to find a homogeneous cartographic representation of two distinct geomorphic regions. Legend adaptations lead us to define three geomorphic domains (see Figure 4.4 and Figure 4.5) consisting of specific morphologies and process dynamics.

- Alluvial plains are extensive in the case of Fez and less developed in Beni Mellal (except for the downstream reach of Day stream). The main mapping efforts focused on delimiting floodplains; the current urban modifications impeded more detailed mapping in Fez (Lasri 2013), while the simple morphology of the downstream Day reach made floodplain mapping sufficient in Beni Mellal.
- Valley bottom and channel morphology is specific to the two study fields. Process mapping of longitudinal and lateral erosion, as well as morphological mapping of active or inherited forms were undertaken (inherited forms are gorges, palaeochannels, while active forms encompass rockfalls in valley bottoms, alluvial bars, erosion scars etc., see Figure 4.4)
- The alluvial fan domain, predominant in Beni Mellal, was mapped in order to distinguish the newer, more active fan zones marked by recent sedimentation and flooding. Palaeochannels were also inventoried as they represent possible

flood concentration transects (Figure 4.4).

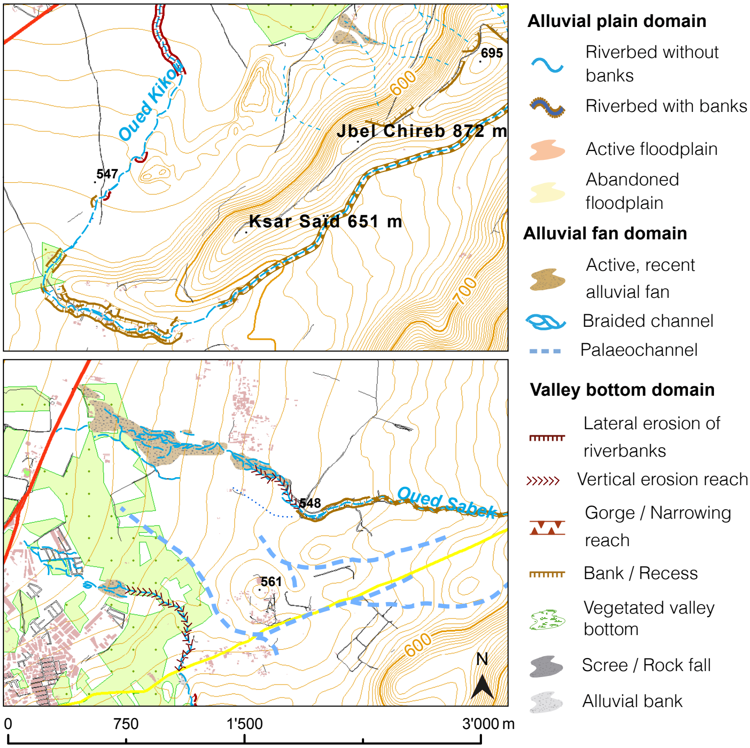


Figure 4.4. Geomorphic elements mapping examples and legend.

The lower Day reach presents an alluvial plain morphology where one can distinguish a main channel and floodplain crossed by secondary flood channels. This area contains and routes floodwaters coming from the Aïn el Ghazi, Sabek and Handak streams. The "spontaneous" yet non-regulated settlement (*douar*) of Nkhila is set in the flood trajectory of Day stream lower reach. It has therefore witnessed several floods during the last decade.

Valley bottoms and channel morphology domain mapping focused on current stream dynamics related to the erosion-transport-deposition pattern in active channels. Incision dynamics characterize the upper Handak and Aïn el Ghazi reaches. Erosional patterns are also visible on the Handak stream upstream of the newly built flood-protection walls as well as on fan portions situated in the upstream proximity of the active fan regions of the Sabek and Aïn el Ghazi streams (Figure 4.5). Incision at the fan apex and *dir* / fan contacts could be related to local base level changes related to mitigation measures and infrastructures (flood-reduction dam and channel deepening and enlargement on Handak stream, construction site for a new flood-reduction dam on Aïn el Ghazi stream). The important incision pattern on the upper Handak stream at the *dir* contact triggered one bridge failure in February 2010 (Photo 4-5a). Base level-controlled incision can equally be witnessed on the Sabek and Ain el Ghazi fan reaches just upstream of the contemporary hydrologic apex (Photo 4-5b). In this case small-scale geomorphic adjustments may take place as a function of evolving active fan sedimentation.

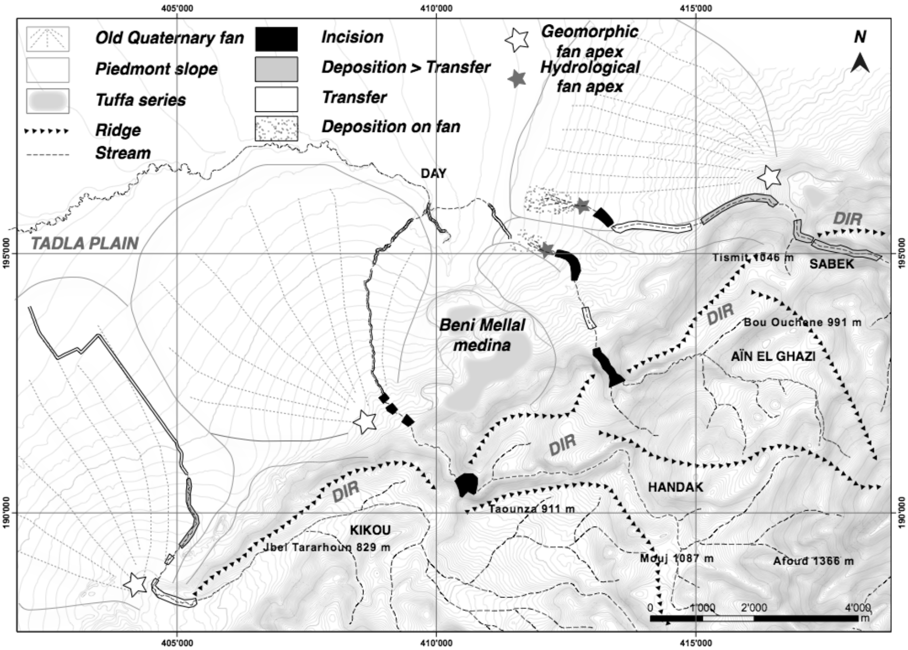


Figure 4.5. Fluvial processes schematic. Erosion – transfer – deposition relationships.

The Kikou stream incises an old alluvial fan: channel evolution is marked by lateral bank erosion. This trend may be related to channel adjustment to increasing discharge; therefore, flood overflow should be avoided. Nevertheless, two exceptions arise: overflow occurs in convex reach curvatures and at existing barrier infrastructures (route, undersized culvert) that aggravate overspill. Lateral erosion is coupled with important gravel accumulations in the streambed on the Kikou and upper Sabek reaches (Photo 4-6a, b).

From a flood hazard perspective, the important available solid load represents an additional threat. Indeed, solid transport was found to have increased during the last years; change was visible between our field trips in 2009 and 2010, as the gravel sedimentation front on the active fan has moved to more distal zones.

The specific alluvial fan morphology impacts the flooding processes and dynamics on our study site, mainly by inducing the typical sheet-flood patterns we witness there. Indeed, once transport capacity regresses and the gravelly load is deposited, sheet floods cover large areas of the northern part of the city, transporting an important suspended load. This natural process, very adapted to the traditional land use of olive plantation where newly added silt increased soil fertility, is now conflicting with the city's rapid urbanization pace and important territorial changes (Photo 4-7).

Photo 4-5. a) Ourbi' bridge failure on the upper Handak reach; b) incision trend on the Aïn el Ghazi fan reach.

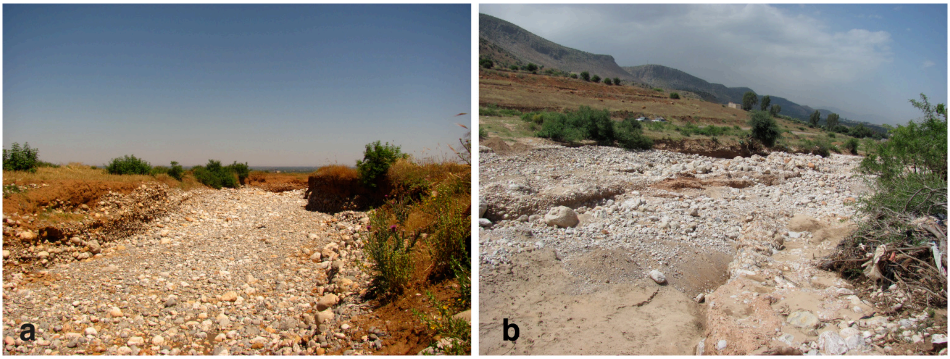


Photo 4-6. a) gravel accumulations on the Kikou fan reach; b) gravel accumulations on the Sabek apex reach.

Photo 4-7. Flood silt accumulation in the Al Massira sector.

Inundation extent and typology

Monitoring known flood events and mapping their spatial extent via geomorphic approaches furnish relevant insights in flood actual and possible behaviour. The extent of floods in September 2009, February 2010 and October 2010 were mapped during field campaigns based on geomorphic flood markers and residents' testimonies. The mapped surfaces also represent field-collected calibration measures for hydraulic flood modelling (discussed in Chapter 6). Jointly, post-flood wetted section estimates based on high water markers were collected at the catchment outlets following monitored flood events, as verification means for subsequent hydrologic modelling. Genetically, floods were classified as follows:

- Overflow inundations due mainly to inappropriate flow sections at several bridges. Small section capacity may be related to unsuited dimensions or to the plug effect of sediments and different accumulations upstream of the structure.
- Torrential inundations on the alluvial fans aggravated at the fan frontal zone by an important sedimentary charge.
- Floodplain inundation, generalized in Fez and restricted to the downstream reach of the Day stream in Beni Mellal
- Other inundation types were identified in the Fez case: static flooding due to water table rise and brutal overflow flooding of flood-protection dams (Lasri 2013).

Flood types are related to morphology specificities (Figure 4.6): in this particular case study, high-energy catchments produce flash floods. Once at the catchment outlet, discharge is conveyed through short channelized reaches to end up in sheet flooding on gently sloping, fossil alluvial fan surfaces. Highly torrential, floods also convey an important solid discharge that threatens certain areas like the Hadouz village at the Sabek stream outlet. On fan distal areas fine sediments are deposited in urbanized areas. Urban infrastructures be it hydraulic or not, complicate the natural pattern by inducing congestion effects that aggravate flood overflows.

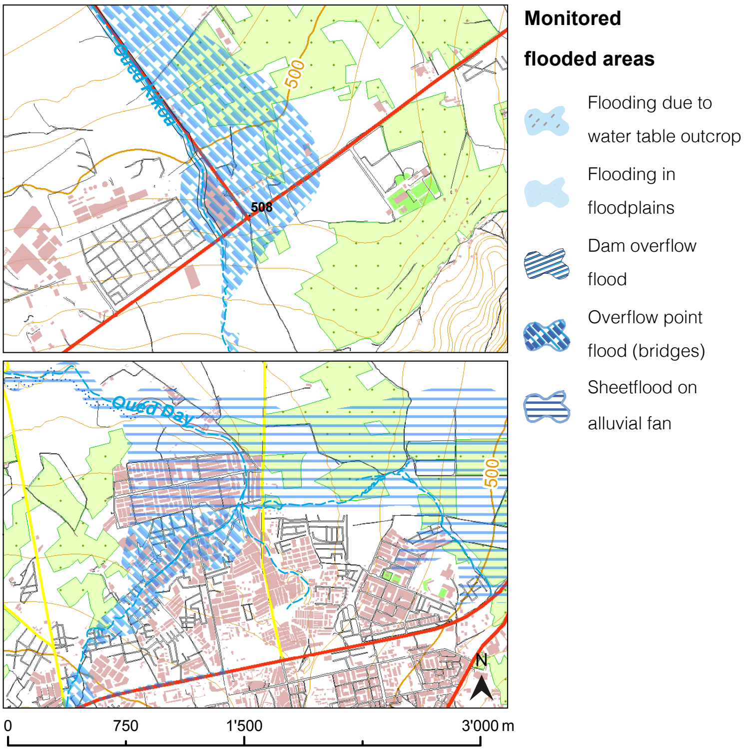


Figure 4.6. Flood areas mapping and typology. Map examples and legend.

Anthropic elements

Urban or hydraulic infrastructure elements (Figure 4.7) may strongly influence flood development, especially in densely populated areas. We inventoried those elements playing an important role in water flow concentration or overspill.

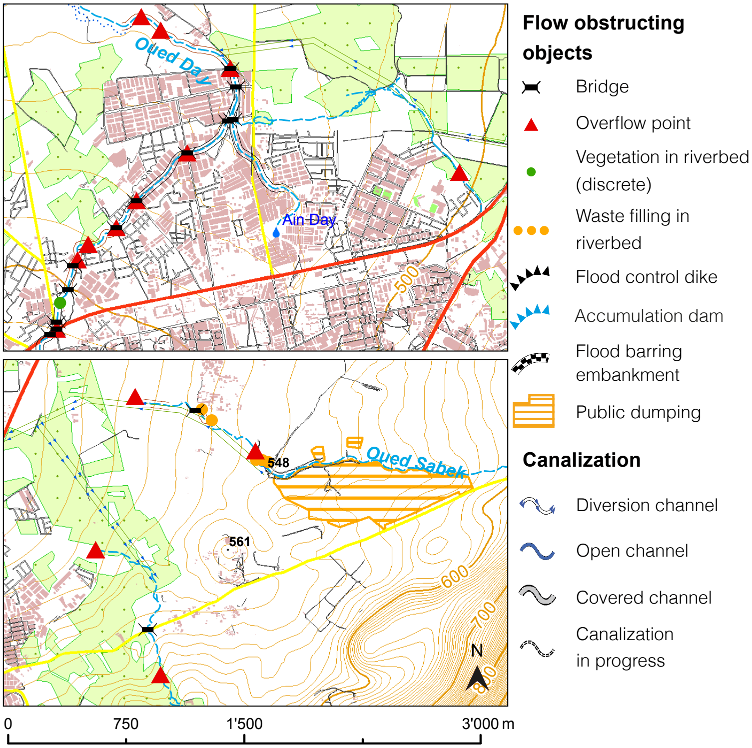


Figure 4.7. Anthropic elements mapping examples and legend.

- Water flow obstructions like flood-reduction dikes are designed for hazard mitigation; unregulated valley-bottom waste disposals or flow-transversal road embankments may produce water depth rise or overflows when flow section capacity is exceeded.
- Bridges, according to their hydraulic radius and congestion conditions may become serious flow obstructions provoking overflow inundations in areas where river flow section capacity is sufficient.

Indeed, undersized bridges and culverts produce overspills at places where stream section could be sufficient for discharge routing; street configurations tend to channelize sheet flows into somewhat urban floods; and barrier infrastructures like route embankments cut flow connections inducing inundation. As the flood mitigation infrastructure was in progress at the time of survey, flood aggravation effects could be noted on the reaches downstream of the built structures. This situation had important flooding consequences in the northern Al Massira district in 2009 and 2010. Undersized bridge overspills are partly related to bad timing in structures building: levee walls and dikes were built before increasing bridge or culvert capacity.

Flood threats can be coupled with additional hazards such as pollution. The Beni Mellal public dumping consists of an open junkyard set in direct proximity with the Sabek streambed, systematically flooded by this stream's high waters. As a consequence, important quantities of waste are driven kilometres away on the fan surfaces. Infrastructure seems to play a primary role in flood development and aggravation in the city of Beni Mellal. We assume that the fast urbanization pace will increase this role in the future, as more conflicting situations will occur between urban and natural systems needs.

Base map

The background map was obtained using spatial information from the Beni Mellal urban plan 1:2'000 dating from 1999. This information was completed using ©2010Cnes/SPOT images provided by ©Google Maps. This spatial information is relevant as a base map for the geomorphic as well as indicative hazard map. It also delivers spatial vulnerability information via land use classes and plays a fundamental role for hydraulic model setting. Topography, urban infrastructure and land use information form the base map.

4.3.3. Main map insights in terms of hazard

The *phenomena* map points out those areas affected by active hydro-geomorphic processes that can be correlated with more intense hazards. Active erosion processes mostly affect communication infrastructures (bridges and the crossing routes due to incision) and marginally built housing facilities set in immediate proximity of the streams (for example bank erosion on Sabek in the village of Hadouz).

Active sedimentation on the alluvial fans as well as re-activated alluvial fan activity on the Sabek and Aïn el Ghazi streams do not affect built areas for now, as they develop in the olive plantation domain. Nevertheless, this renewed activity has resulted in damage to the plantations, ensuing in material losses. Moreover, the fan activity has constrained building in the area: a planned housing allotment downstream the Aïn el Ghazi hydrological apex never was finalized as a result of systematic gullying along the traced construction lines. One should notice that the aggradation front on Sabek stream was visibly moving downstream towards the Fez-Marrakech main road during the survey period. That is, sedimentation problems may arise in the future at this level.

Sheet flooding on the gently sloping alluvial fans affected large areas, mostly of agricultural character. One might note that some of these areas are assigned to building purposes in the master plan. Along the urbanized reaches of the fours streams, the street network, as well as some *seguias* played an important role in orienting floodwaters, which resulted in increased depth and velocity, and subsequent damage.

The anthropic elements of the phenomena map introduce the problematic of under-calibrated bridges and culverts that artificially produced flooding, even when the stream capacity was sufficient to convey floodwaters. Many such overspills occurred on the highly urbanized Handak reach resulting in flooding of the houses set close to the stream and intense sedimentation. Moreover, the mitigation measures undertaken on the upstream reach had provoked an intensification of flooding in 2009 on the downstream reach, mainly in the densely populated Al Massira district.

In conclusion, the *phenomena* map and field survey undertaken during the mapping stage allow us to draw an outline of the flood hazard realities in Beni Mellal. This insight is extremely useful for the subsequent assessment stages, as a means to verify and control indirect assessment results such as modelled floods.

4.4. Discussion

4.4.1. Geomorphic map contributions and limitations

Contributions

Maps representing geomorphic and anthropic elements directly related to natural hazards and more specifically to floods represent important tools for **hazard identification** and subsequent mitigation procedures. The *phenomena* map accomplishes several aspects of hazard reckoning.

- First, the map provides a **synoptic, graphical view** of the flood hazard premises on the given territory; it allows better understanding of flood triggers, aggravating elements and consequences from a spatial point of view. In our study case, the hazard-related *phenomena* map shed light on the spatial relationships between geomorphic elements (e.g. fan apex), existing infrastructure (bridges, culverts) and flood type and extent.
- Second, these spatial elements allow **hazardous region delimitation** and to a certain extent their classification; therefore, further hazard assessment efforts may be focussed on those areas expected to witness flooding. For example, the alluvial apex zones, the portions of alluvial fan that face flooding, or the stream and infrastructure interactions represent hazardous areas mapping focused upon.
- Finally, *phenomena* mapping was designed to compensate for other hazard identification approaches (i.e. past **event inventories**) due to the lack of documentation. Hence, field memory was estimated to compensate archives memory.

Furthermore, the *phenomena* map is a valuable **verification** tool for flood **hazard assessment**, supplying it with justification means.

- **Hydro-geomorphic behaviour** comprehension provided by this mapping approach is essential for sound hazard assessment in data scarcity conditions specific to the studied region. Geomorphic flood markers that testimony for past system behaviour and allow predicting future dynamics. Indeed, hazard assessment methods will be oriented by field knowledge in order to reach more realistic hazard estimations.

- Moreover, geomorphic mapping of flood extents and other flood-related estimates offer useful **calibration** criteria for mathematical hazard assessment approaches (Chapters 6 and 7). In our study case, specific verification criteria were mapped according to methods that interrelate modelling to field geomorphology.
- Finally, this map emphasises the fundamental role **urban infrastructure** plays in flood generation, aggravation or control. This is an important issue for further flood assessment via mathematical models as flood modelling accuracy in urban areas is scale-dependent: therefore, spatially small structures may influence flood development in ways mathematical models may not assume. In this context, field collected verification means become essential for correct hazard predictions.

Limitations

From a **methodological** point of view, two limitations must be noted.

- First, we note a significant deviation from the Swiss method in that the *phenomena* map we established **does not represent event intensity**; that is, process activity, age, or intensity were not specifically represented to assess hydro-geomorphic behaviour intensity. Still, distinctions between active / inherited forms were undertaken in the map legend. We can justify this choice by the fact that the *phenomena* map we designed is not intended to substitute mathematical hazard assessment approaches.
- Second, map legend choices were oriented towards a **cartographic compromise** between two different fields: Fez and Beni Mellal. Inevitably, cartographic accuracy losses occurred in this process.

Circumstantial limitations may have also hindered the quality of the work.

- We note first the **short monitoring time** and the **lack of contextual information** about flood history in the city of Beni Mellal. Indeed, the flooding problematic is recent in the studied area and little documentation is available. The short monitoring duration in these conditions brought us to analyse flood events that actually occurred during the two monitoring years and to consider them as reference events without having the possibility to assess their importance in terms of statistical recurrence time or intensity. Subsequent flood modelling would shed light on the relative intensity these events actually attained.
- Second, monitoring **interfered** with the current active flood **mitigation strategy** adopted by the local authorities. We were therefore constrained to limit the map's validity to the stage July 2010 and not to take into account the planned mitigation structures in mapping. On the positive side, natural hydro-geomorphic mapping of those areas untouched by the planned mitigation measures provided an important amount of hazard-related knowledge that

may further inform about residual risks associated with active mitigation measures.

- Finally, **poor** cartographic **data quality** and / or **actuality** imposed important data updates in the establishment of the base map. Moreover, cartographic adaptations imposed by poor data precision (mainly DTM availability) resulted in modifications that violate map precision to respond to map coherence needs (Figure 4.8, Reynard et al. 2013).

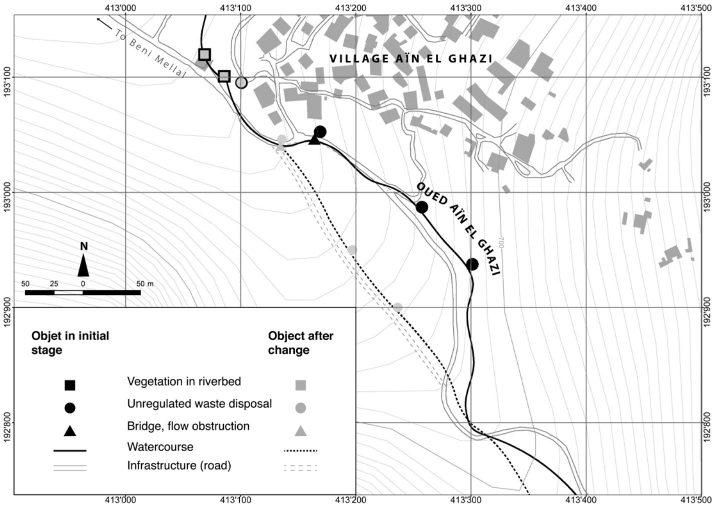


Figure 4.8. DTM low quality imposed cartographic modifications that violate map precision. From Reynard et al. (2012).

4.4.2. Method applicability

As stated above, hazard-related *phenomena* maps represent sound hazard identification tools. The main focus of this project is to achieve knowledge transfer of the Swiss hazard map methodology to Morocco. Swiss method reproducibility is nevertheless subject to specific methodological adaptations, in order to respond to different hydro-climatic, geomorphic and socio-economic conditions. This chapter presents a possible adaptation, based on thorough state of the art of the existing hazard-related geomorphic mapping research. Gathered knowledge has been confronted with field conditions and specific local mitigation strategies. The experience we collected through this project can improve potential future application of this method in similar natural and social conditions. Several points can better orient future users.

- First, this is an interdisciplinary approach. That is, geomorphologists skills are essential for field elements mapping and interpretation; however, a hydrologist view is necessary when it comes to assessing geomorphic markers pertinence for hydrologic / hydraulic model verification. It is, therefore, fundamental that map designers with multiple scientific and decisional backgrounds achieve the mapping process in a collaborative way.

- Additionally, good collaboration with local planners and agencies involved in hazard mitigation is essential in order to access locally available spatial and eventually hydro-meteorological data. The necessity for collaboration must be petitioned to planners and decision-makers as final product quality largely depends on input data.
- Furthermore, a good compromise between methodological research, field investigations and other field characterization approaches (e.g. remote sensing, DTM investigation) must be achieved in order to avoid time-consuming work procedures. Good practice guidelines for focused geomorphic mapping, available methods descriptions could be an asset for faster, cost-effective field surveys.
- Moreover, one must note that the proposed approach only explored flood hazard; in other environments, multiple hazards may threaten one region. Depending on hazard types (landslides, avalanches etc.), geomorphic mapping may become essential for hazard recognition and assessment. In this case, closer adaptations of the Swiss legend for *phenomena* mapping may prove appropriate. Process intensity interpretations may establish the base for subsequent hazard maps.
- Finally, field-collected knowledge of natural processes and their interactions to humans is essential at each hazard management stage. Therefore, field surveys should include all those elements relevant for further hazard assessment and mitigation. We responded to this requirement by integrating hydrology-oriented approaches to the mapping process.

4.5. Conclusion

Hazard identification in the field is essential for further risk management approaches. This chapter focus was set on adapting the Swiss methodology for hazard-related *phenomena* mapping to the Moroccan realities. Methodological adaptations related to hydro-climatic, morphologic and anthropic factors were undertaken according to the existing literature developed for similar environments. Cartographic effort was confronted to the challenge of representing two morphologically different environments (Fez and Beni Mellal).

The resulting *phenomena* map reflects, on one hand the importance of alluvial fan morphology for flood characteristics in the city of Beni Mellal, and on the other hand the essential role urban infrastructures play in flood genesis and aggravation. *Phenomena* map provides a synoptic view of all the elements involved in flood development; it helps delineate the hazard-related areas for further focus on flood hazard estimations and provides them calibration criteria via flood extent mapping and geomorphology-based discharge estimates. However, this map is time-constrained to the July 2010 stage, despite on-going active mitigation procedures during the survey time. It has though the advantage to account for a large panel of flood-related natural processes *before* protective infrastructures building. Therefore, the map is equally a good indicator for residual risks in those areas subject to active mitigation measures. Overall, we advise that the map represents a valuable document for flood hazard recognition and subsequent hazard assessment verification. Its reproducibility in similar environments depends mainly on collaborative, interdisciplinary geomorphic and hydrologic approaches to field surveys. Likely, good collaboration between scientists and local authorities and data-owners is essential for producing high-quality, realistic maps.

The flood-related *phenomena* map drawn for the city of Beni Mellal responds to the needs for thorough understanding of natural and anthropic flood hazard triggers and provides a sound basis for further hazard assessment in terms of flood scenarios and their consequences at the urban level.

In the following chapters, we use flood hazard assessment approaches, at the catchment level via hydrologic modelling, and at the urban perimeter level via hydraulic flood intensity and extent modelling. Coupled with field collected calibration criteria, these approaches intend to simulate set recurrence flooding scenarios in order to assess flood hazard. Then, we finally come up with an indicative hazard map for the urban perimeter of Beni Mellal.

5. Hydrological modelling

Flood hazard mitigation, whether passive or active, takes into account worst-case scenarios of extreme events. In order to accord protection objectives and flood scenarios, these extreme events are classified according to their occurrence probability, as it has been demonstrated that flood frequency and intensity are negatively correlated. Therefore rare events (with low occurrence probability) are more intense. Generally, measured data referring to rare or extreme events (e.g. the 100-year return period flood) is not available, especially in mountainous regions, where gauging networks are still scarce or very recent. This is where modelling plays its role as it allows us to simulate extreme flood events, informing us about their possible consequences in terms of hazard.

In this chapter, we focus on flood modelling on the four catchments that drain the city of Beni Mellal. The objective is to obtain flood hydrographs corresponding to events of 20, 50 and 100-year recurrence periods. These reference events were selected according to the Moroccan hazard mitigation practice (ADI, ABHOER 2006).

This work is divided in two thematic directions. First, we model known, recent flood events, in order to choose the most appropriate hydrologic model to the catchments concerned. Field-collected flood marks allow us to verify the obtained results. Then, we extrapolate these findings to more rare flood scenarios, in order to obtain flood hydrographs for events of low, medium, and high intensity. Finally, these results form the inputs for a hydraulic model that will precise hazard in terms of flood extent and intensity at the urban level for given occurrence scenarios. The latter issue will be discussed in a subsequent chapter. In terms of organization, this chapter makes firstly a short introduction to hydrologic modelling. Then, it presents the data processing needed to feed the model, the methods used and finally the results and their validation. A discussion section closes the chapter.

In the Beni Mellal province, flood hazard protection is treated by the Oum-er Rhbia Catchment Agency (*Agence de basin Hydraulique de l'Oum-er-Rhbia*, ABHOER). According to the Water Act 1/1995, the Agency has the legal obligation to elaborate the hydrologic studies and to build the infrastructure necessary to flood protection on its action area. We used in this work some of the Agency's study results and data that it graciously provided.

5.1. General framework

5.1.1. Model typology

Models represent schematics of real-life phenomena. They can be mathematical outlines of that phenomenon, or physical, scaled representations of it. Most hydrological models are mathematical (Musy & Higy 1998), as they tend to explain reality by solving a series of equations or mathematical relations.

Depending whether model outputs depend on inputs or on random conditions, models will be **deterministic** or **stochastic**. Deterministic models are (1) **empirica**l if their relations stem in observations (e.g. the Rational method, Musy & Higy 2004); (2) **statistical** if they tend to extrapolate observed behaviour to other time spans following a distribution function (e.g. the Gumbel distribution model, Gumbel 1954); (3) **conceptual** if they simplify and idealize catchment behaviour or (4) **mechanist** if they tend to closely represent reality by the greatest number possible of the fluid movement equations for a given catchment (Musy & Higy 1998). Among hydrologic models, most are conceptual ones (Wagener et. al 2002). They allow us to predict and to reconstruct natural phenomena like floods through simplified schematics of a catchment natural behaviour.

From a temporal point of view, models can be **event based** (e.g. 100-year return period flood model) or **continuous** when they simulate processes for a long period of time. Continuous models have the advantage to account for antecedent catchment moisture conditions.

Depending on the way catchment is spatially represented, models are: **lumped** if the catchment as a whole is described by a series of parameters, or **distributed** if parameters describe processes at the cell level.

Finally, depending on the way catchment response relates to inputs, models are **linear** (e.g. unit hydrograph method) or **non-linear**. Many models make a linearity assumption even if flow is basically non-linear (Musy & Higy 1998).

5.1.2. Model choice versus parsimony

Models tend to simplify reality. Yet, they can become very complex as soon as they intend to explain more accurately the real processes (Beven & Binley 1992, Young et al. 1996, Wagener et al. 2002), therefore increasing uncertainty. For instance, the path that leads from a rainfall event to a certain runoff amount at the catchment outlet implies processes at the surface (interception, ponding, evapotranspiration, direct runoff), at depth (infiltration, percolation, subsurface runoff, water table variation) and interface processes (runoff from water table rise). Modelling each of these processes increases overall complexity. We keep in mind the parsimony principle (Young et al. 1996, Wagener et al. 2002), requiring that complexity should be proportional to the available data and the model's needs. Finally,the necessary processes for modelling semi-arid hydrological behaviour need to be clarified.

Semi-arid region hydrology is influenced by important spatial and temporal rainfall variability, often expressed in short and intense convective storms (Pilgrim et al. 1988, Hernandez et al. 2000, Wheater 2002). In conditions of sparse vegetation and shallow or crusted soils, interception and infiltration are limited, while excess overland flow dominates (Pilgrim et al. 1988, Osterkampl & Friedman 2000, Wheater 2002). Moreover, due to rapid runoff onset, flood hydrographs are steep, characterizing flash floods (Pilgrim et al. 1988, Wheater 2002, Bahat et al. 2009).

Hydrological modelling in semi-arid catchments is challenging mainly as: a) semi-arid catchments are seldom gauged; b) spatial-temporal rainfall variability is high and difficult to monitor; and c) few rainfall-runoff models were developed in semi-arid conditions, where processes of excess infiltration dominate (Bahat et al. 2009). Thus, empirical methods that estimate catchment potential peak discharge are often used to characterize the hydrological behaviour of semi-arid catchments (El Hames 2012). A number of studies questioned the model complexity necessary in semi-arid catchments (Bahat et al. 2009, McIntyre & Al-Qurashi 2009, Ghavidelfar et al. 2012). The specific spatial-temporal rainfall variability results in uneven process distribution within a catchment that might require the use of a distributed model. Nevertheless, in conditions of data scarcity, the use of a too complex model may not be beneficial. Studies in semi-arid catchments seem to prove that distributed and lumped models may perform equally well (Bahat et al. 2009, Ghavidelfar et al. 2012).

In this case study, the existence of a surface and subsurface karst may locally induce losses during intense rainfall events, but these are difficult to determine in absence of karst quantification (De Vera 1984).

We applied the conceptual framework proposed by Wagener et al. (2002) Figure 5.1, to modellers and users as a means of estimating the necessary model complexity. In this respect, model complexity should be tuned according to the performance needed to achieve the model's purpose, as long as model uncertainty is kept in acceptable limits.

Due to the limited amount of available data and to the aim of this work, that is, obtaining realistic flood hydrographs for subsequent flood hazard mapping, we need a **deterministic conceptual model** able to represent the main hydrological processes in the studied catchments and to realistically predict outlet flood hydrographs. In a temporal point of view, we wish to predict flood events: an **event model** is thus required. In a spatial point of view, we opt for a **lumped catchment model** due to data scarcity and therefore to the need for parsimony. Finally, to account for the possibility of reproducing this study results on other locations in developing countries, we look for **open-source** hydrological solutions.

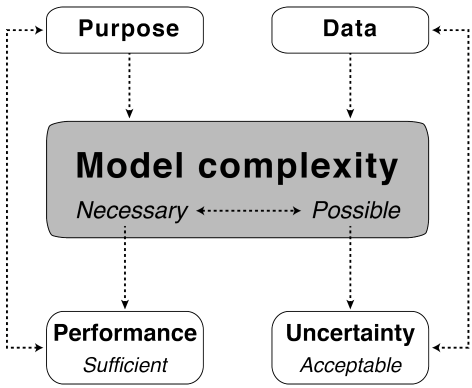


Figure 5.1. Model complexity: a function of needs and availabilities. Modified from Wagener et al. 2002.

The USACE© HEC-HMS open-source modelling facility (USACE 2000) provides several hydrologic methods on a conceptual model basis representing catchments globally as reservoirs linked by hydrologic reaches. In this context, hydrologic processes (i.e. infiltration, interception, runoff) are described by several methods ranging form empirical to physically based models. For its availability, important method choice, cost-benefit efficiency and relative user-friendliness, the HEC-HMS modelling facility responds to our requirements. Moreover, this open-source facility can enable the re-use of our cartographic method in similar environments.

To respond to the parsimony principle, we chose to model only the fundamental processes necessary for obtaining realistic outlet discharge hydrographs (Figure 5.2). These processes are **infiltration** and **direct runoff**, which represent two fundamental components of the water cycle during a flood event. We assume that **infiltration** represents the most important part of the "lost" water in the outlet hydrograph and we include vegetation and karst **interception** in some infiltration models as an initial condition parameter. In the same way, only **surface direct runoff** was accounted for, as surface and subsurface hydrological processes in semi-arid catchments are defined as disconnected (Pilgrim et al. 1988). Indeed, the relatively small soil depth and sparse vegetation conditions of the studied catchments allowed us to assume that direct runoff is the most important surface process responsible for floods.

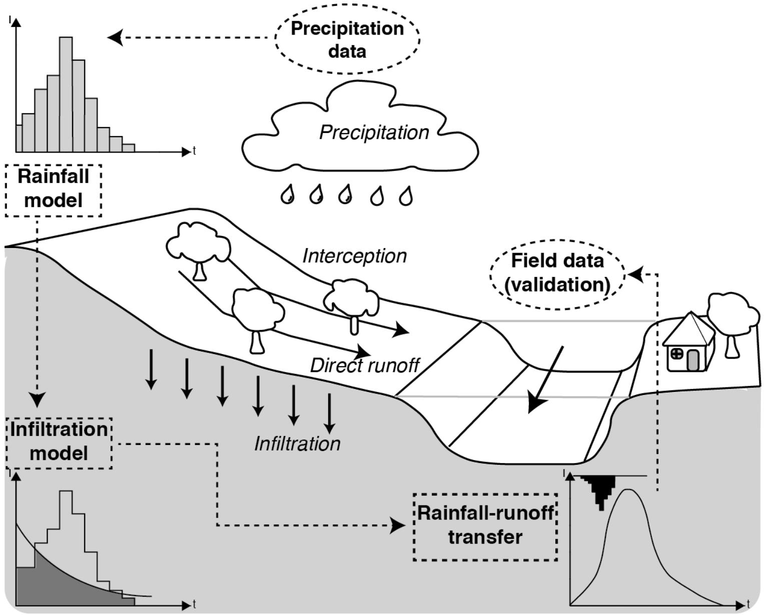


Figure 5.2. From rainfall to runoff: the necessary processes modelled.

Hydrologic modelling consists of four steps (Musy & Higy 1998):

- **Data pre-processing**: during this stage, catchment modelling and input data creation (e.g. rainfall model) are undertaken.
- **Model calibration** tends to find the best model parameter estimates that fit on measured observed data and to measure at some extent simulation errors. Sensitivity analysis is usually undertaken at this stage in order to assess parameters weight in results variability. As no measured data is available for the catchments draining the city of Beni Mellal, no classical calibration is feasible. Yet, field-collected high water marks

allowed us to obtain peak discharge estimations that were used to "calibrate" the model. We carried out sensitivity analysis on the chosen parameters in order to account for their respective roles in final output variable values.

- **Model validation** consists in applying the finally fitted parameters on other hydrologic events and therefore validating the model's results. At this stage, uncertainty analysis should be undertaken as a measure of model confidence span for future utilization.
- **Final utilization** can be constrained by initial and boundary conditions choice. It also gives free space for model verification in real-life conditions.

5.2. Data pre-processing

5.2.1. Catchment model

Four catchments drain the city of Beni Mellal: Sabek, Aïn el Ghazi, Handak and Kikou (see Chapter 3 for description). We extracted altitude contours from the 1:50'000 topographic map in order to obtain a DTM (Digital Terrain Model) through interpolation. The 1:50'000 topographic map represents the most precise elevation data available for the study area. Streams were burned in during this process. Catchment pre-processing was performed using ArcHydro Tools in ESRI ArcMap. The obtained filled DTM, flow direction, flow accumulation and stream datasets were processed using the HEC-GeoHMS extension of ESRI ArcMap in order to create a HEC-HMS compatible catchment model.

Catchment	Ghazi	Handak	Sabek	Kikou1	Kikou2	Kikou3
$A[km^2]$	15.83	29.71	20.83	22.35	24.38	8.1
CN	75.97	75.92	79.32	74.48	76.49	85.11
$T_{c[h]}$	0.82	2.15	1.41	0.90	1.31	0.63
$\%\,Imp$	15.94	20.56	27.65	18.89	23.97	14.06

Table 5.1. Catchment area (A), Curve Number (CN), concentration time (T_c), and impervious surface percentage ($\%\,Imp$). Kikou catchment is subdivided in three sub-catchments (Kikou1, Kikou2, Kikou3)

Due to poor input data and to the relatively small study area, we decided to model catchments globally: their parameters represent the area-weighted average of spatially distributed values (Table 5.1). In contrast, a distributed model would solve equations on a grid basis, the result reflecting spatial variability of inputs. The relatively small catchments of Aïn el Ghazi, Sabek and Handak rivers were modelled as single sub-basin units, while the Kikou catchment was divided into three sub-basins.

Catchment time of concentration (Table 5.1) represents the maximum duration a water drop needs to travel from a catchment point to the outlet (Musy & Higy 2004). We calculated catchment time of concentration using the TR-55 methodology (NRCS 1986). In this method, the time of concentration T_c is calculated as the sum of various travel times related to specific flow types: sheet flow, assumed to occur on catchment backwater areas, shallow-concentrated flow occurring on slopes, and finally open channel flow. Travel time $T_t(h)$ is calculated as:

$$T_t = \frac{L}{3600V} \tag{5.1}$$

Where $L(ft)$ = flow length; $V(^{ft}/_{s})$ = average velocity. Therefore,

$$T_c = T_{t1} + T_{t2} + T_{t3} \tag{5.2}$$

Where $T_{t1}(h)$ = sheet flow travel time; $T_{t2}(h)$ = shallow-concentrated flow travel time, $T_{t3}(h)$ = open channel flow travel time.

Curve Number CN can be calculated for different catchment moisture conditions: CN 1 for dry conditions, CN2 for average conditions, and CN3 for moist conditions. In this study, we computed average Curve Number values (Table 5.1).

5.2.2. Soils and land use mapping

Soil type and distribution have great influence on the infiltration processes. No soil surveys were undertaken in this region mainly because of its low agricultural potential. The only soil map available is the SOTER soil database, at 1:8'500'000 scale, which classifies the soils *in situ* as "complex"(FAO 2001). At this scale, the SOTER database was irrelevant for our study, and a soil dataset needed to be produced.

Soils are typical of the Mediterranean hydro-climatic region, with a xeric regime due to the strong seasonality, where soil weathering is effective only during the wet winter season. Soil hematite-induced reddening is a direct effect of the seasonal pattern (Yaalon 1997, Verheye & De la Rosa 2005). The mainly carbonaceous substratum in the Mediterranean region as well as steep topography represent the other important factors in Mediterranean pedogenesis. Yaalon (1997) states also that Saharan dust supplies important quantities of fine material into pedogenesis, therefore compensating for the low weathering residuals of hard carbonaceous rocks. As a consequence of the specific pedogenetic process, soils in the Mediterranean are characterised by high clay content and slope-determined maturation stage and depth. From a hydrologic point of view, these attributes are important in deducing soil runoff potential.

Soil was conceptualized by Jenny (1941) as a function of pedogenetic factors:

$$s = f(cl, o, r, p, t, \dots) \tag{5.3}$$

Where s = soil, cl = climate, o = organismus, r = relief, p = parent material, t = time. This functional factorial model found several applications and quantification methods over time (McKenzie & Ryan 1999, McBratney et al. 2003). It is used in different forms for digital soil mapping, with the assumption that the pedogenetic factors or some related variables can predict soil classes or properties for a given site on the basis of environmental correlation (McKenzie & Ryan 1999).

In order to estimate field-related hydrologic soil properties, we roughly applied the factorial model to the four catchments draining the city of Beni Mellal. As stated above, the Mediterranean climate produces a unique soil generation pattern that stays halfway between tropical and temperate pedogenetic areas. Therefore, the climate factor helped narrowing down the classification only to typical Mediterranean soils. The vegetation cover was used as a soil integrity measure because denser vegetation preserves soil from erosion. Relief or topography was resumed to slope that is an erosion variable essential for understanding soil depth and maturation stage. Parent material is very important as a genesis factor *per se* and for the hydrologic properties of soils that are tightly related to substratum properties. Time factor was omitted as it would be difficult to implement and unnecessary to the practical purposes of this work.

We used a semi-quantitative decision-tree (Figure 5.3) in order to map soil classes according to the factorial model. Discrimination parameters were based on literature retrieved knowledge on soil genesis and evolution. Slope threshold was set to 20° for separating steep terrain from level and rolling one. This is justified by the erosive and runoff-generating role of steep slopes (SSDS 1993) that impact pedogenesis (Yaalon 1997). Parent material information was extracted from the geologic map 1:100'000. Geologic information was resumed to 4 rock types based on their composition and cohesiveness: 1) massive limestone, 2) marly limestone and recent carbonaceous alluvium, 3) marls and marly alluvium and 4) crusted puddings and conglomerates. Vegetation cover was classified in two broad classes: relatively dense vegetation (forest and dense shrub) and sparse or inexistent vegetation. As pointed by Boer and Puigfäbregas (2005), patchy vegetation on hillslopes induces greater water and sediment yields than homogeneous vegetation cover. Land cover information was retrieved from a 2009 GoogleMaps image.

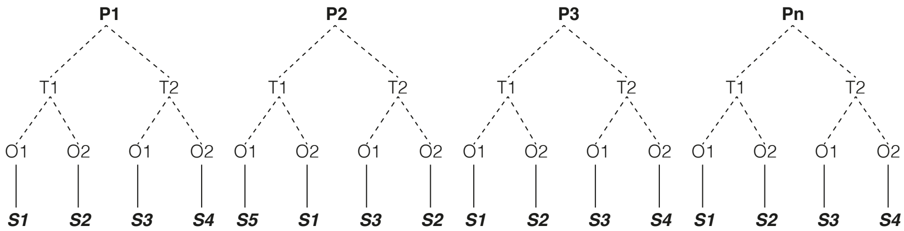


Figure 5.3. Decision-tree for broad soil classification. $P_{(1...n)}$ = parent material; $T_{(1...n)}$ = time; $O_{(1...n)}$ = organismus, here vegetation; $S_{(1...n)}$ = resulting soil type.

For this study, we rewrite Jenny's equation (5.3):

$$s(cl) = f(\,o, r, p \dots), \qquad (5.4)$$

as the climate factor is the main knowledge source available to us for soil classes prediction and as time factor was left unused.

For hydrologic use, the National Resources Conservation Service (NRCS) of the U.S. Department of Agriculture resumed soil properties to four runoff potential groups (NRCS 2007, Table 5.2). We classified the soil classes we had obtained accordingly, in order to use this information in hydrologic model parameter setting (Table 5.3).

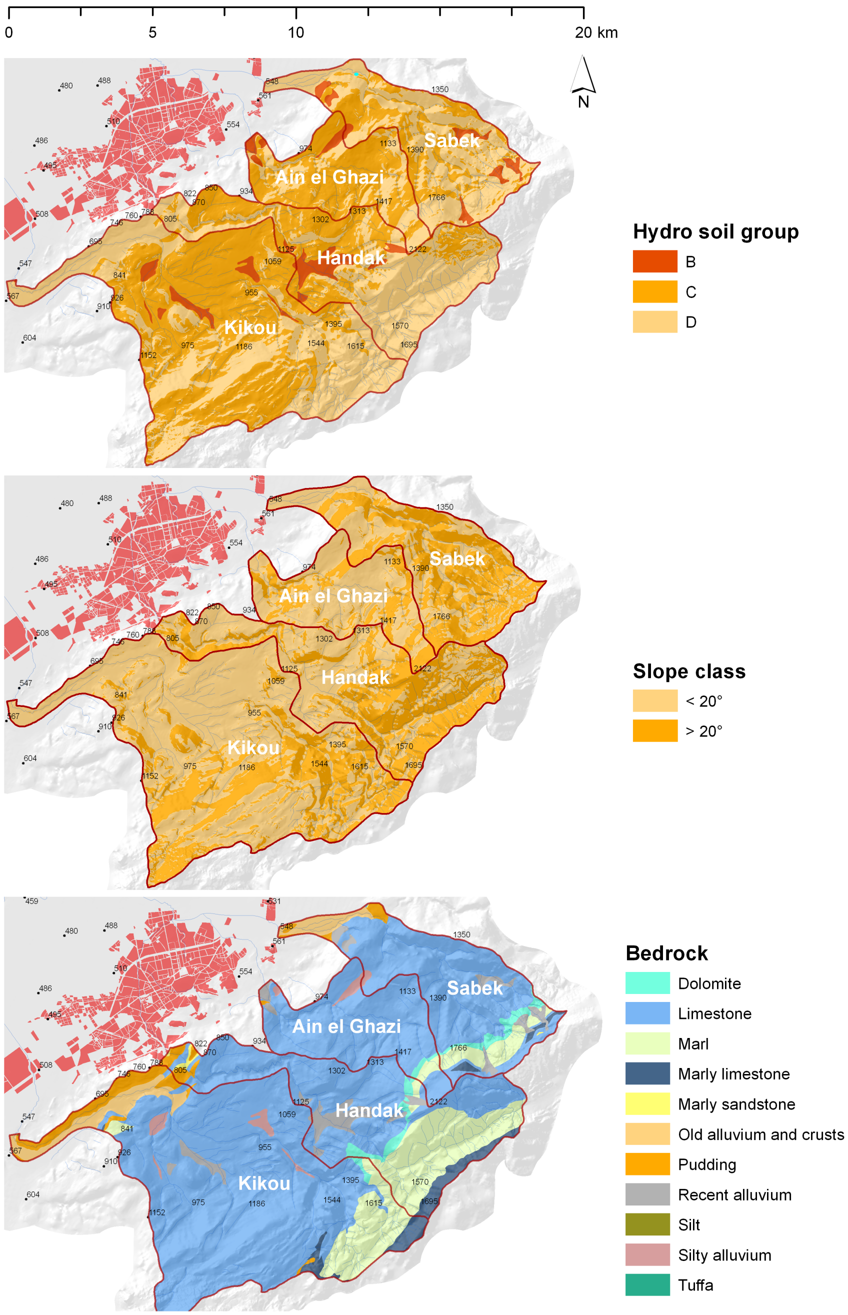


Figure 5.4. Soil map and the base data.

Hydrologic soil group	Runoff potential	Clay content	Depth to impervious layer	Soil depth	Texture
A	Low	< 10%	> 50 cm	> 100 cm	Sandy, gravelly
B	Moderately low	10 - 20%	> 50 cm	> 100 cm	Loamy sand, sandy loam
C	Moderately high	20 - 40%	> 50 cm	> 100 cm	Clay loam, silty clay loam
D	High	> 40%	< 50 cm	-	Clay

Table 5.2. Hydrologic soil groups and their properties. From NRCS (2007).

For the study area, we defined soils according to the factors described above (Table 5.3). First, on hard limestone and level to sloping conditions there are relatively well-weathered red-to-brown coloured soils from the *Xeralf* group, according to the U.S. Soil taxonomy elaborated by the NRCS (1999). These soils are rich in clay and other fine material and present strong decalcification. They are generally shallow due to the poor weathering residuals of the hard carbonaceous substratum (Verheye & De la Rosa 2005). They may show an A-B-C-R profile in an evolved stage, where the B-horizon may be strongly elluviated and contain 2:1 clays (Yaalon 1997). From a hydrologic point of view and according to the NRCS methodology (NRCS 2007), these soils can be classified in the C/D hydrologic soil group, formed of 20 to 40% clay and an impervious layer at about 50 cm depth. Soils on crusted old quaternary fans are considered to be in the D group as they have a very shallow impervious contact (Figure 5.4).

Second, soils on softer carbonaceous substratum (marly limestone and marl) and level to rolling slopes may be less well weathered as the parental rock is mostly mechanically disintegrated. These soils may not reach the A-B-C-R profile; they will rather contain an A-C-R horizon pattern. Therefore, they remain skeletal and their chemical composition is close to the parent material features. They can be categorized in the *Entisol* group of the U.S Soil taxonomy; for Mediterranean conditions, the soil taxonomy describes *Entisols* according to their genetic factors rather than using the xeric moisture feature. *Entisols* are mineral and do not have diagnostic horizons. These soils can be classified in the D hydrologic soil group with more than 40% clay and shallow impervious substratum.

Bedrock	Slope	Vegetation	Soil class (soil taxonomy)	Hydrologic soil group
Hard limestone	S < 20%	all	Xeralf	C/D
Crusted old alluvial fan	all	all	Xeralf	D
Marly limestone, marl	all	all	Entisol-	D
Hard limestone	S > 20%	all	Skeletal	D
Marly limestone, marl	S > 20%	all	Xerorthent	D
Recent alluvium	S < 20%	all	Rhodoxeralf	B

Table 5.3. Pedogenesis criteria, expected soil taxonomy class and assigned hydrologic soil group for the soils in the studied catchments.

On steeper slopes soil generation is overpassed by erosion (Yaalon 1997, NRCS 1999). Therefore, soils on hard carbonaceous rocks remain skeletal, as no time is available for weathering. They may present an A-R profile and very shallow depths. On softer limestones and marls, erosion produces skeletal, patchy soils with a badland aspect where vegetation will hardly colonize. From a taxonomic point of view we expect these soils to be part of the *Xerorthent* category of the *Entisol – Orthent* group. NRCS (1999) states that *Xerorthents* may occur on moderate to steep slopes, on weakly cemented rocks or very thin regolith on hard rocks. Due to their high clay content, we consider these soils to have a great runoff potential and, therefore, classify them in the D hydrologic group, even though slope could offer them a better drainage potential.

Finally, on level alluvial zones, soil geneses is stimulated, thus thicker soils, with A-B-C-R profile are likely to form. We assigned these soils to the B hydrologic group.

Soil groups and land use information were integrated as decision-making factors for the choice of hydrologic method parameters in the process of infiltration modelling.

5.2.3. Rainfall data sources

Northern Atlas is part of the Mediterranean hydro-climatic region, characterized by strong contrast between dry and hot summers and mild and wet winters (Hooke 2005). Mediterranean strong seasonality triggers complex rainfall-runoff processes on the basis of specific catchment wetting and drying. Changes in land cover and especially the deforestation / forest renewal pattern have great influence on hydrologic behaviour, runoff being greatly related to its patterns (Latron et al. 2009).

Topography plays a major role for catchment hydro-meteorological behaviour in Mediterranean mountainous areas, often confronted to convective storms that occur especially (but not only) during the hot season. These storms may be generated by small convective cells (10 to 50 km wide), or be part of greater convective structures (Camarasa Belmonte 1993). The study site in Beni Mellal is subject to this type of hydro-meteorological events, mostly in early autumn and late spring. When rainfall records are available for a region, a rainfall-runoff relationship can be established for each catchment in order to obtain runoff values for different events. One can model known, historical events, in which case the model accuracy may be determined by a comparison between measured and simulated data of rain and discharge. Yet, it is seldom that extreme historical events could be monitored. Nevertheless, for practical purposes like flood protection structure plans or flood mapping, extreme events must be simulated.

Design storms

When no historical flood monitoring is available, hypothetical storm events are to be elaborated and fed into the hydrological model in order to obtain the required recurrence flood hydrographs. Most of these rainfall models are based on the Intensity-Frequency-Duration (IFD) curves (Musy & Higy 1998, Alfieri et al. 2008). IFD curves represent the rainfall pattern for a given monitoring point. They are derived from rainfall frequency analysis and represent the probability of a given rainfall intensity to occur given a duration (i.e. a return period) (Bedient & Huber 2002). Commonly, IFD-derived design storms are rectangular (Alfieri et al. 2008), with a duration chosen most likely in relationship to the catchment's time of concentration T_c and a constant intensity read on the IFD curve for the desired recurrence time T_p and the chosen duration. The main disadvantage of this method consists in its failure to represent rainfall structure in time, but it may represent the only alternative to recreate low occurrence-high intensity rainfall events when only daily rainfall data is available. Other methods tend to redistribute rain intensities in order to obtain more realistic hyetographs (e.g. Cordery et al. 1984). We used the IFD curve methodology to obtain a rectangular hyetograph for rainfall recurrence periods of 20, 50, and 100 years. The IFD curve was elaborated for the Beni Mellal meteorological station. Rain intensity was adjusted using the Montana law (ADI 2004):

$$I(t,T) = a(T) * t^{b(T)}. \quad (5.5)$$

Where I = average rain intensity for duration t, T= recurrence time; a= IFD intensity parameter; b = duration parameter.

The two parameters, a and b define rainfall intensity for a given recurrence period and rain duration. The parameter a is very dependent on the T recurrence time; b is somehow dependent on the regional context (ADI 2004, Table 5.4).

According to Alfieri et al. (2008), who simulated a 10-hour flood event with different design storm hyetographs, rectangular hyetographs tend to underestimate flood peak discharge, while a hyetograph using the catchment Lag time would be more accurate: in the cited study, for a Lag of 3 to 7 hours, errors were constant. For our study case, where T_c is usually lower than 2 hours, we consider that a storm duration equal to the catchment Lag is best suited for modelling set recurrence events. So, we chose the hyetograph duration equal to each catchment's time of concentration T_c.

Recurrence time T	Parameter $a(^{mm}/_{h})$	Parameter b
2	12.4	0.675
5	23.2	0.635
10	30.3	0.625
20	37.1	0.619
50	45.9	0.614
100	52.4	0.612

Table 5.4. Montana parameters for the Beni Mellal IFD curve. From ADI (2004).

Several authors warn that the relationship between rainfall T_P and flood T_Q return periods is not linear: generally $T_Q \leq T_P$ (Bedient 2002, Blöschl & Viglione 2009). The ratio T_Q/T_P depends on several factors such as the relationship between catchment time of concentration and storm duration or catchment wetness (Blöschl & Viglione 2009, Viglione et al. 2009). Therefore, we expect to model floods derived from given return period rainfall events instead of given return period floods. Moreover, the lack of discharge gauges on the studied catchments hinders any flood frequency analysis that could inform us about set flood return periods events. Osterkampl & Friedman (2000) point out that in semi-arid catchments, the flood to rainfall return time disparity tends to produce higher return time floods for lower return time rainfall events, as compared to more humid catchments. This fact might be explained by poor infiltration patterns specific of the semi-arid zone.

Known flood events for a better catchment understanding

Lack of measured data impedes performing normal calibration procedures in the studied catchments. Simulating known, field-monitored events, and further verifying model results using hydro-geomorphological evidence (e.g. high water marks) could compensate this difficulty (Gaume & Borga 2008). This alternative approach to classical calibration can help to improve model tuning by providing "calibration" means for parameter analysis. Moreover, field-monitored floods can improve catchment knowledge, transferable to floods simulated out of purely theoretical storms. We monitored three flood events that took place during field trips in 2009 and 2010.

As described in Chapter 3, the ABHOER-owned rain gauges are situated outside the studied catchments and measure solely daily rainfall. We needed though locally distributed data at a finer timescale to simulate rain events in the flash flood-prone catchments in this study.

Satellite-borne precipitation estimates could fill data gaps in mountainous, ungauged catchments (Hong et al. 2007, Nikolopoulos et al. 2010) and therefore provide hydrological models with precipitation inputs. We used three-hour rainfall data made available by NASA's TRMM (Tropical Rain Measuring Mission) project (Huffman et al. 2009) to model the events that took place during the fieldwork in Beni Mellal. The 3B42 rainfall dataset offers a 0.25° resolution (about 25 square km) on a three-hour base since 1998 (Hong et al. 2007, Huffman et al. 2009). This data is estimated from other satellite-measured parameters and it has proved its efficiency in flood assessment studies led in medium (Nikolopoulos et al. 2013), and large-scale basins (Su et al. 2008, Yong et al. 2012). Nikolopoulos et al. (2010) pointed out that satellite-borne precipitation estimates errors propagated in hydrological model outputs are resolution and scale-dependent; therefore, in small catchments and for flood application temporal scales, this error can be important.

Indeed, not all the recorded events, often very localized, may be visible in the rainfall datasets. From the three field-recorded events, only two could be corroborated with rainfall information in the TRMM dataset (14 February 2010 and 11 October 2010, (Figure 5.5 and Figure 5.6). The 14 February 2010 event occurred during a relatively rainy period related to winter low-pressure zones underlined by the High Atlas topographic effects. The relatively short 11 October 2010 rain event occurred in an early autumn situation marked by convective activity.

By exploring these two rainfall events and the recurring floods, we take into account two typical Mediterranean hydro-meteorological situations: winter rainfall seasons when catchments are relatively moist, and short and intense convective storms that are likely to trigger fast catchment response and provoke flash floods.

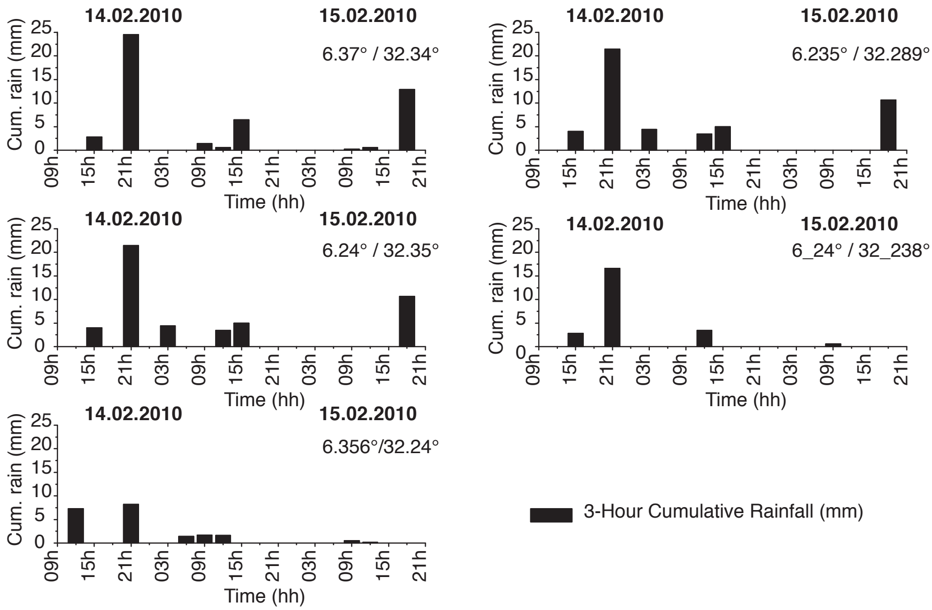


Figure 5.5. Cumulated 3-hour rainfall values (mm) for the February 2010 event at the five TRMM cell centre locations.

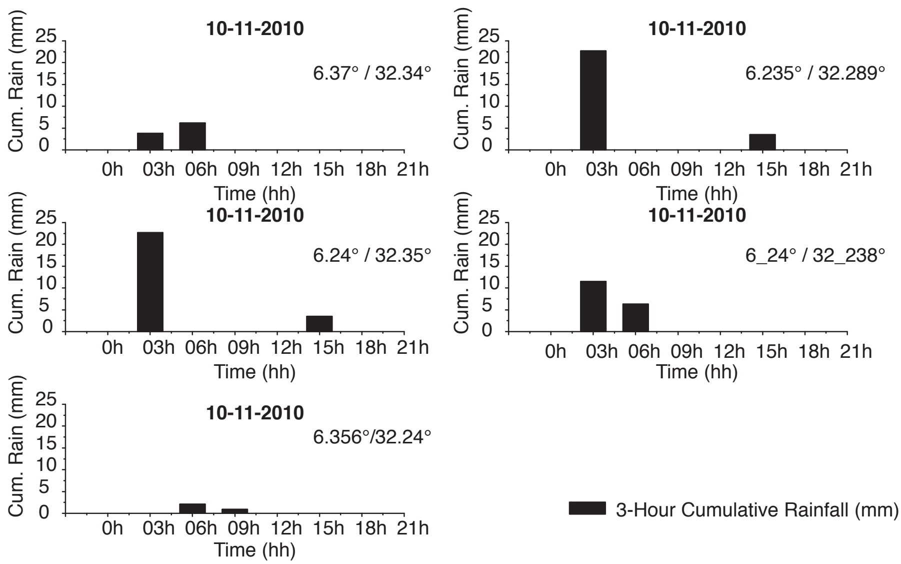


Figure 5.6. Cumulated 3-hour rainfall values (mm) for the October 2010 event at the five TRMM cell centre locations.

The four studied catchments area is covered by five TRMM cells of 0.25° resolution. The 3-hour cumulative rainfall values corresponding to the five cell centres were retrieved for each rainfall event (coordinates of the cell centre points are marked on Figure 5.5 and Figure 5.6). These values were considered as five point gauges that were subsequently entered in a HEC-HMS meteorological model based on the inverse distance squared scheme (USACE 2000). A time step of 20 minutes was chosen to discretize the 3-hour rainfall data.

5.3. Model calibration

The first, most important and time-consuming stage of the modelling process is calibration, which consists in fitting a hydrologic model's results to measured data. In the case study, many unknown elements have to be accounted for. First, no measured discharge data is available for a classical calibration to be drawn. Moreover, model calibration requires data from an important number of events. In this study, owing to the lack of measured calibration data and the need to monitor flood events using field campaigns, the choice of events was restricted to those that occurred during this study fieldwork trips in 2009 and 2010. Finally, hydrological processes at the catchment level are poorly known. Therefore, in this section, we test different models and "calibrate" them according to field-collected peak discharge estimates. We do so in order to find the best-suited model for the studied catchments in terms of output and respect of the catchment properties.

5.3.1. Infiltration methods description

Three infiltration methods were tested on the four catchments draining Beni Mellal to simulate the October 2010 event. These methods apply to the so-called pervious surfaces, in contrast to impervious surfaces, which allow the entire amount of rainfall to be transformed into runoff (USACE 2000). On pervious surfaces, rainfall is fractioned into interception, infiltration and excess precipitation that form direct runoff. Percolation and subsurface runoff complicate this design. Unlike in humid or temperate environments, surface and subsurface hydrology is seen as disconnected in semi-arid regions (Pilgrim et al. 1988). In semi-arid catchments similar to the studied ones, hortonian flow is thought to occur. In other terms, soils infiltration capacity is rapidly exceeded and overland flow sets on. Infiltration remains, therefore, the most important control for direct runoff in these areas. We tested three infiltration methods, available in the HEC-HMS program.

The Soil Conservation Service (SCS) developed the ***Curve Number* methodology** *(SCS CN,* Figure 5.7a) in the United States for small, ungauged catchments, primarily to assess land use change impacts on direct runoff (Rallison & Miller 1981). It is assumed to be the most widely used method for storm runoff calculation (Van Mullen 1991). Numerous hydrological observations on experimental catchments scattered all over the United States led the SCS to propose an empirical relationship between retention capacity and catchment environmental characteristics. This relationship was resumed to a single non-unitary parameter, the Curve Number (CN), which spans from 30 for very pervious surfaces to 100 for water surfaces. The SCS based this method on the assumption that the sum of the cumulated rainfall and cumulative infiltration curves is constant (Figure 5.7b).

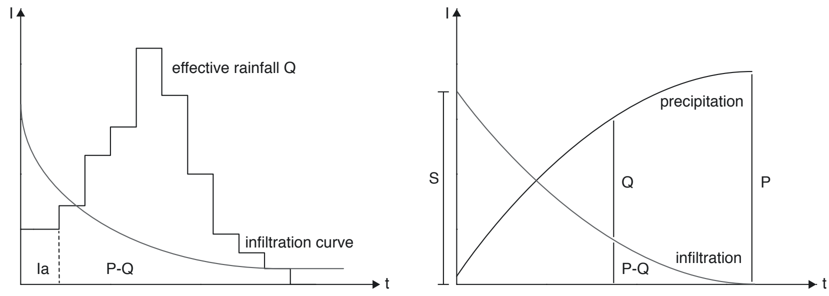


Figure 5.7. a) SCS infiltration model: Ia = initial abstraction; Q = effective rainfall; P = total cumulated precipitation; P-Q = infiltrated rainfall; I = rainfall intensity; t = time. b) SCS assumption: the sum of cumulative rainfall and cumulative infiltration curves is constant: S = maximum potential retention. From Musy & Higy (1998).

Therefore, a simple triangle geometry relationship can be established:

$$\frac{Q}{P} = \frac{P - Q}{S} \tag{5.6}$$

Where: Q = excess rainfall (mm); P = cumulated total precipitation (mm); S = maximum potential retention (mm). Therefore, by adding the initial abstraction I_a (mm) that represents the amount of water retained by interception processes , equation 5.6 can be written as

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \tag{5.7}$$

The SCS empirically associated I_a to the maximum potential retention S as:

$$I_a = 0.2\,S \tag{5.8}$$

The SCS Curve Number (CN) is a measureless parameter relating cumulative rain to excess precipitation curves. The SCS published lists of CN values for different soil types, and land cover classes and for different antecedent moisture conditions. CN is related to S and can be calculated by an empirical approach as:

$$CN = \frac{25400}{S + 254} \tag{5.9}$$

In the HEC-HMS program, the SCS CN infiltration method requires the Curve Number parameter as an input. The CN methodology addresses also infiltration on the basis of the SCS assumption. Cumulative infiltration F (mm) can be written as:

$$F = P - I_a - Q \tag{5.10}$$

By using equation (5.7), cumulative infiltration F can be expressed as:

$$F = \frac{S(P - I_a)}{P - I_a + S} \tag{5.11}$$

And the infiltration rate $i(t)$ (mm/h) is derived as:

$$i(t) = \frac{d(F)}{d(t)} = \frac{S^2}{(P - I_a + S)^2} * \frac{d(P)}{d(t)} \tag{5.12}$$

For this study, we deduced Curve Number values according to the soil and land use information available. For each catchment we calculated one area-averaged Curve Number value using the HEC-GeoHMS extension in ESRI (Table 5.1). The SCS Curve Number method also requires the proportion of impervious areas in each catchment in order to deduct them from infiltration rate calculations. We defined bare rock surfaces as impervious, while all the other surfaces were considered to be more or less pervious.

The *Initial and Constant infiltration* method assumes soil infiltration potential to be constant during a rain event (Figure 5.8). An initial abstraction is added to account for antecedent moisture conditions and catchment characteristics. Initial and Constant Loss is a parsimonious model that simplifies soil hydrologic behaviour. Yet, it might underestimate excess precipitation for large rain events (Musy & Higy 1998).

The initial abstraction parameter accounts for antecedent catchment moisture conditions, surface ponding and interception processes. We consider interception to be the most important element for Initial abstraction estimation. Studies on Mediterranean vegetation interception rates show very contrasting results between study sites and even between and inside study plots (Carlyle-Moses 2004, De Jong & Jetten 2007, Baloutsos et al. 2010). In order to estimate this initial parameter values, we used the available information on catchment land use and corroborated it with literature estimates (De Jong & Jetten 2007, Bandaragoda et al. 2012). Initial abstraction values were obtained on a surface-averaged base. Further, sensitivity analysis by parameter variation was performed on the infiltration model to find the best fitting values in reasonable limits in terms of model credibility and expected outlet discharge.

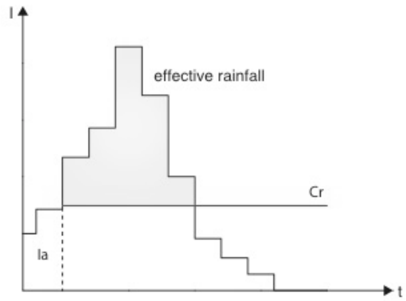


Figure 5.8. Initial and constant infiltration principle. From Musy & Higy (1998).

The constant infiltration rate parameter can be related to soil type and texture. Skagg & Khaleel (1982) published constant infiltration rates corresponding to the four hydrologic soils groups of the NRCS (2007). In order to estimate entry parameters, we used the soil information previously prepared for this project (Section 5.2.2). Constant rate parameters were chosen according to Skagg & Khalleel (1982, Table 5.5) for C/D and D hydrologic groups. For the C/D group lowest range values were used; as for the D group, mid-range values were chosen. This choice is justified by the natural context of the studied catchments where very shallow soils and scarce vegetation induce relative surface impermeability. Sensitivity analysis was performed on the model in search of best constant rate estimates. The result of this analysis and its implications in terms of model uncertainty will be further discussed in the results section of this chapter. The impervious area proportion was calculated similarly to the SCS CN method.

Hydrologic soil group	Texture	$C_r(^{mm}/_h)$
A	Sandy, gravel	7.62 – 11.43
B	Sandy loam	3.81 – 7.62
C	Clay loam	1.27 – 3.81
D	Clay	0 – 1.27

Table 5.5. Constant loss rate (C_r) ranges by hydrologic soil group. From Skagg & Khaleel (1982).

The *Green-Ampt infiltration method* is an adaptation of the Darcy law for unsaturated flow and one of the first physically based infiltration models. In 1911, Green and Ampt modelled soil as a homogeneous infinite column where wetted soil is sharply delimited from non-wetted soil by the wetting front (Figure 5.9).

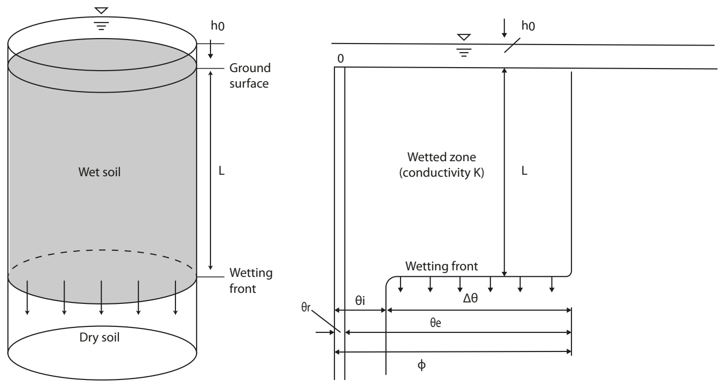


Figure 5.9. Green-Ampt conceptual model. From Chow et al. (1988). Variables: ϕ = soil maximum moisture content; θ_i = moisture content below the wetting front; $\Delta\theta$ = moisture deficit, L = wetting front depth; K = saturated conductivity.

Infiltration i can be written for a soil column of unit cross-section as the total gradient including the capillary suction S_f as to express dryness in lower soil levels (Brevnova 2001). If we exclude the small h_0, infiltration is written as

$$i = K\frac{S_f + L}{L} \tag{5.13}$$

Where K = saturated conductivity (mm/h), S_f = capillary suction (mm), and L = wetting front depth (mm). On the other hand, cumulative infiltration I (mm) yields

$$\mathrm{I} = L(\phi - \theta_i) \tag{5.14}$$

Where $(\phi - \theta_i)$ (mm/mm³) = the change in moisture content. Therefore,

$$L = \frac{I}{(\phi - \theta_i)} \tag{5.15}$$

In order to calculate the infiltration rate i_t (mm/h), equation 5.13 can be written as

$$i_t = \frac{dI}{dT} = K \frac{S_f(\phi - \theta_i) + I}{I} \tag{5.16}$$

The terms K, S_f, and $\phi - \theta_i$ represent input parameters for the Green-Ampt method as it is implemented in HEC-HMS, along with an initial moisture content that should be estimated from antecedent moisture conditions at the catchment level and the impervious area percentage as for all the infiltration methods described here.

Rawls & Brakensiek (1982) analysed data concerning over 1300 soils and more than 5000 horizons in order to relate soil properties to the Green-Ampt parameters. They found the best fit with soil texture classes and published value ranges for the Green-Ampt parameters. We used values for clay (hydrologic group C/D) and silty clay (hydrologic group D) textures respectively. Sensitivity analysis was performed on each parameter in order to find the best value fitting for the expected outputs. This approach led to choose very small K values (10% of the initial values) in order to attain the expected discharge peaks. This issue shall be discussed further in this section as it represents an important point when choosing Green-Ampt method for catchments similar to our study site.

5.3.2. Rainfall-runoff transfer method

Excess precipitation calculated by infiltration models inputs rainfall-runoff models in order to obtain an event hydrograph. We chose the Snyder Unit Hydrograph (UH), an empirical model whose basic assumption is that runoff is a linear process (Figure 5.10a). This choice is justified by a need for parsimony: Snyder UH parameters are relatively easy to calculate. Moreover using one rainfall-runoff transformation method allowed us to compare the role of infiltration models in the final output hydrographs. In unit hydrographs, total runoff is calculated by convolution of multiple runoff units issued from multiple basic effective rainfall units (Musy & Higy, Figure 5.10b). Snyder (1938) found an empirical relationship between rainfall duration t_r and catchment lag t_p as $t_p = 5.5t_r$. For a different UH duration, the relationship will be defined by

$$t_{pR} = t_p - \frac{t_r - t_R}{4} \tag{5.17}$$

Where t_p = catchment lag (h); t_r = rainfall duration (h); t_{pR} = lag of expected UH (h); t_R = duration of expected UH (h).

HEC-HMS sets t_{pR} equal to the specified time interval in order to obtain the expected lag in equation 5.15 (USACE 2000). Then it calculates the UH peak using

$$\frac{U_{pR}}{A} = C \frac{C_p}{t_{pR}} \tag{5.18}$$

Where U_{pR} = peak of expected UH (m^3/s); A = catchment drainage area (m^2); C = conversion constant (2.75 in metric system); C_p = UH peaking coefficient.

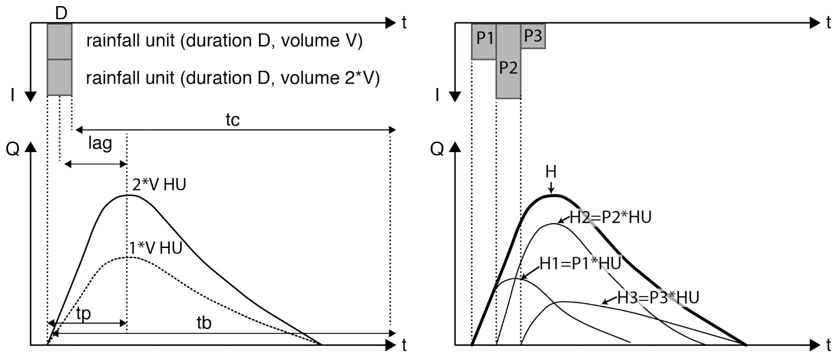


Figure 5.10. Unit hydrograph (UH): a) UH principle of linearity and b) UH convolution. From Musy & Higy 1998.

Snyder UH can be regarded as parsimonious, as it requires only two parameters: catchment lag t_p, related to its concentration time, and peaking coefficient C_p, a measureless hydrograph shape parameter. We obtained the Lag parameter using the TR55 methodology integrated to HEC-GeoHMS. Sensitivity analyses on the peaking coefficient led us to choose values higher than 0.5, which produce steep hydrographs. This shape is specific of flash floods that are known to occur on the studied torrential catchments. Values of C_p up to 0.8 were calculated for mountainous catchments (USACE 2000).

5.3.3. Hydrograph "calibration" on field collected data

In ungauged catchments, classical calibration process that consists of fitting simulated hydrographs to measured ones is impossible. This leads hydrologists working in semi-arid ungauged catchments to avoid models needing calibration: in this respect, many Moroccan catchments are modelled using empirical formulas and regional approximate models. Yet, as Gaume & Borga (2008) point out, hydro-geomorphologic markers may provide information on flood depth and spatial extent after important flood events. We suggest that this method is highly applicable for small intermittent watercourses in semi-arid areas where discharge between two rain events tends to be null.

In order to calibrate the model to real event measures, we undertook post-flood field campaigns to collect hydro-geomorphologic flood markers. High water marks in river cross-sections were used to estimate wetted cross section and wetted perimeter (Figure 5.11). Cross-section roughness coefficient and relative water surface slope were estimated in the field. Then, discharge was calculated using the Manning formula:

$$Q = K * S * R_h^{2/3} * i^{1/2} \tag{5.19}$$

Where: Q = flow discharge (m³/s); K = Manning roughness coefficient; S = wetted section (m²); R_h = hydraulic radius (m); i = water surface slope (m/m).

To better link the modelled and the real event, information about the event's timing characteristics was collected from inhabitants living close to the streams. This helped us to broadly verify the hydrograph shape and the peak time as from cross sections only peak discharge could be estimated. Where possible, splash marks on bridges were collected, in order to estimate water velocity. According to Gaume & Borga (2008), splash marks can be corroborated with water velocity (Table 5.6):

Velocity	In m/s	Splash height
moderate	< 2 m/s	< 20 cm
high	2 - 4 m/s	40 - 80 cm
extreme	> 4 m/s	> 100 cm

Table 5.6. Splash marks height and corresponding velocity estimations.

We used this relationship to obtain discharge values for neighbour cross-sections, using the discharge formula and further compared these values with the high water marks estimations:

$$Q = S * V \tag{5.20}$$

Where: V = water velocity (m/s)

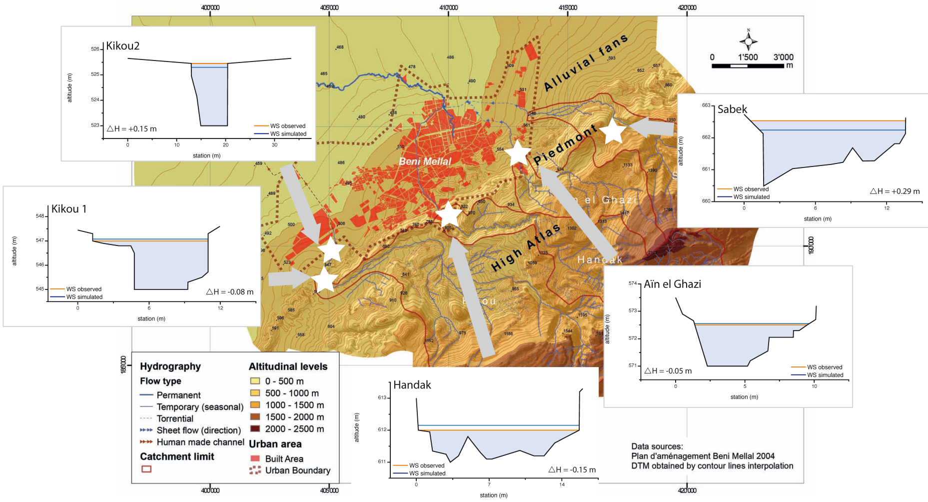


Figure 5.11. Location of control cross-sections. High water marks estimates (red) and model-simulated ones (blue). Data collected after the 11 October 2010 event.

Model fitting could therefore be performed only in terms of peak discharge and partly in hydrograph peaking time. For the study practical purpose, these estimations are acceptable, as flood hazard maps depict maximum flood extension and water depth, which are correlated to peak discharges. The values obtained by the field estimates method were used as calibration values for model fitting.

5.3.4. Parameter sensitivity and calibration

In this section, we describe the calibration process for the infiltration methods presented above. We selected peak discharge as a comparison criterion, as it represents the only hydrograph element that could be estimated in the field, using high water marks. Therefore, parameters resulting in peak discharges close to the field-estimated values were considered in the final parameter selection. The lack of measured flood hydrographs hinders more sophisticated calibration approaches that measure error dispersion between the model and calibration datasets (e.g. R coefficient of determination, or the Nash-Sutcliffe accuracy coefficient, Nash & Sutcliffe 1970).

In order to understand the effects that parameters might induce to model functioning and, therefore, to outputs, we used parameter sensitivity analysis. We performed a one-factor-at-the-time (OFAT) analysis on the infiltration and rainfall-runoff transformation methods. The OFAT method consists of changing the values of one variable at the time and analyse its effects on the output (Morris 1991, Mishra 2009). It can be used in decision-making at an early model stage in choosing the most appropriate method, or at a later stage as a general model uncertainty descriptor.

First, an initial OFAT analysis was performed on all methods by multiplying each parameter by 0.5 and 2. This allowed us to **reject the SCS CN** method as inappropriate for our study case, as the output flood hydrograph showed strongly underestimated peak discharges when compared to peak discharges estimated by the field method (Figure 5.16). Even though CN values were relatively high, the SCS CN method obtained peak discharges two times smaller than the other methods.

This could be explained by the event intensity and shortness in time, and especially by SCS CN assumption that infiltration rate depends on rainfall rate (Smith & Eggert 1978 cited in Brevnova 2001, Hjelmfelt 1980, Figure 5.12) so that rainfall peak is correlated to infiltration peak. This method, albeit parsimonious, could not correctly estimate runoff in the Beni Mellal catchment.

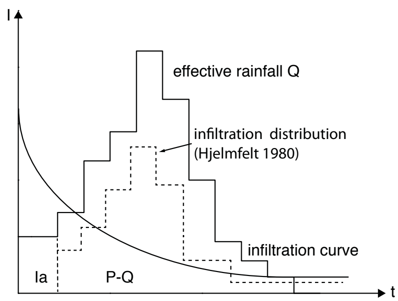


Figure 5.12. The CN SCS method and infiltration rate distribution as depicted by Hjelmfelt (1980).

For the two remaining methods, a second more refined OFAT analysis was performed. The variable change pattern was chosen as a multiplication function of the initial parameter by 0.5, 0.75, 1.25, 1.5, 1.75 and 2 for parameters whose values permitted it. For parameters spanning in limited ranges, a uniform variation pattern was chosen accordingly. This allowed us to have a relatively broad view of each parameter's effect on the output.

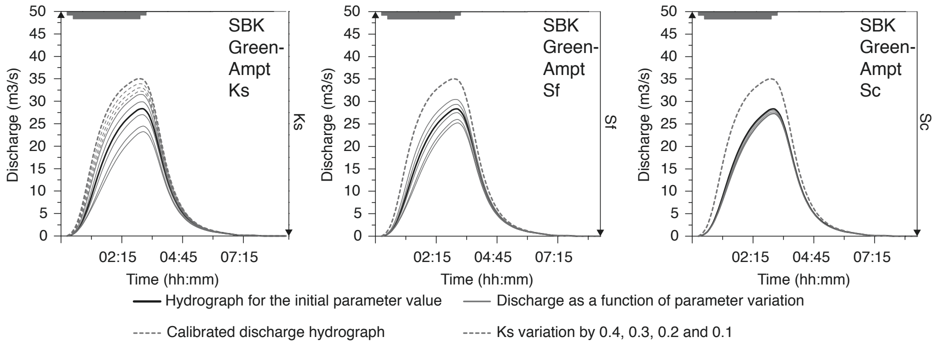


Figure 5.13. Green-Ampt parameter role in flood hydrograph calculation. Example for the Sabek catchment. K_s = hydraulic conductivity; S_f = capillary suction front; S_c = saturated moisture content.

For the **Green-Ampt** method, we tested the saturated hydraulic conductivity K_s, capillary suction front S_f, and saturated moisture content S_c, which is equal to soil porosity. The results (Figure 5.13) show us that:

- K_s is very sensitive and acts directly on the hydrograph peak. By multiplying K_s by 0.5, 0.75, 1.25, 1.5, 1.75 and 2, we could not obtain peak discharges comparable to the field estimated ones. We therefore enlarged the parameter variation range by 0.4, 0.3, 0.2, and 0.1. Depending on catchments, values of $0.2K_s$ or $0.1K_s$ were necessary in order to attain the expected peak flood discharge values.
- S_f is relatively sensitive and acts on hydrograph peaking time. We did not enlarge the variation range for this parameter because its lower sensitivity will influence less output hydrographs. Moreover, this parameter is a function of soil porosity and has no real physical base *per se*.
- S_c can be considered to have low sensitivity. It does not influence hydrograph shape. Variation values for S_c were chosen inside the possible value range for clay and loam clay (0.425 to 0.5).

K_s was found to be the most sensitive parameter for the Green-Ampt model and the main hydrograph peak control; S_f comes in second place. These findings correspond to the results of other studies (Tiscareno-Lopez et al. 1993, Brevnova 2001). K_s could only correctly predict hydrograph peak with very low values. To understand these findings, we have to look back to the Green-Ampt initial assumptions. That is, the model envisages soil as an infinite, homogeneous column where wet and dry soil is delimited by a sharp wetting front, S_f, which is not a physical distance measure but a function of soil porosity and water content.

Liu et al. (2011) investigated the applicability of Green-Ampt for shallow boundary conditions like shallow bedrock or groundwater table. They state that the real infiltration process for shallow soils consists in that the suction front S_f progresses in soil depth until reaching the shallow bedrock or impervious layer, then infiltration ceases. They propose to set K_s to very low values in order to compensate for the model's failure to account for shallow boundary conditions. Sensitivity analysis on the

Green-Ampt parameters brought us to use the same strategy. In semi-arid conditions, shallow soils and short and intense convective storms tend to reproduce this effect (Pilgrim et al. 1988, Hernandez et al. 2000). This study shows that the Green-Ampt infiltration method can be used for semi-arid environments where shallow soils prevail by significantly reducing the saturated conductivity parameter.

We applied the OFAT technique on the **Initial and Constant Loss** method parameters initial abstraction I_a and constant loss rate C_r by multiplying them by 0.5, 0.75, 1.25, 1.5, 1.75 and 2 (Figure 5.14).

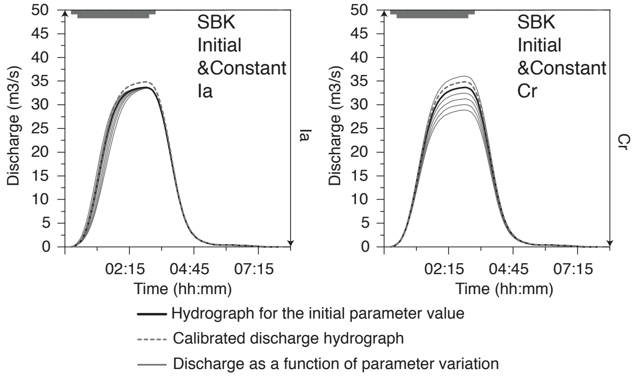


Figure 5.14. Initial and Constant Loss parameter role in flood hydrograph calculation. Example for the Sabek catchment. I_a = initial abstraction; C_r = constant loss rate.

The graphical results show that:

- I_a is not very sensitive and it acts mainly on the peaking time. This can be explained by the fact that in the Initial and Constant Loss method, no runoff is produced until the I_a condition is fulfilled.
- C_r is relatively sensitive and it acts on the peak discharge. Indeed, once the I_a condition is fulfilled, the model will remove a constant amount of water to account for infiltration processes at the catchment scale. By tuning this parameter we could calibrate our model to the known peak discharges previously collected in the field.

The sensitivity analysis showed that the initially set I_a and C_r parameters produced peak discharge values close to the calibration ones. This proves that these field-related parameters can predict in a realistic way the hydrologic processes in semi-arid catchments similar to the studied ones.

Finally, we used OFAT as a decision-making tool in choosing the best-suited **Snyder Unit Hydrograph** parameters (Figure 5.15). As lag time had been calculated for each catchment from field data, only the peaking coefficient C_p was analysed so that we could obtain the most appropriate hydrograph shape for these flash-flood prone catchments. So, we chose higher C_p for steeper hydrographs with short times of concentration and a fast time to peak as well as fast decrease times.

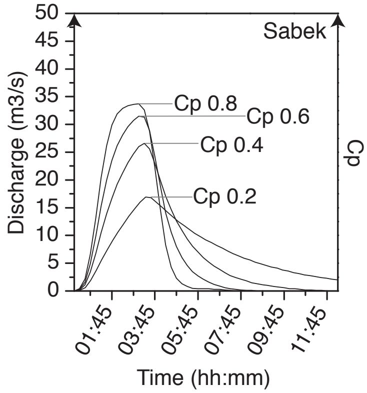


Figure 5.15. The effect of peaking coefficient c_p on flood hydrograph. Example for the Sabek catchment.

The OFAT sensitivity analysis was performed using a relatively small number of simulations. More sophisticated uncertainty analysis that would estimate the effects of multiple parameter variation were not taken into account, for several reasons. First, "calibration" data is represented by single values of peak discharge, and not calibration datasets; thus, datasets dispersion could not be estimated. Then, these values result from field estimations, and not gauging. Indeed, we propose ranges of estimated peak discharge and not unique, measured ones. Finally, the number of parameters is sufficiently small; therefore, sophisticated techniques are not required. Parameters chosen according to the sensitivity analysis are presented in Table 5.7.

Method	Green-Ampt			SCS CN	Initial and Constant Loss		Snyder Unit Hydrograph	
Parameter	$K_{s[mm]}$	$S_{f[mm]}$	θ_{mm/mm^3}	CN	$I_{a[mm]}$	$C_{r[mm/h]}$	C_p	Lag$[h]$
Ghazi	0.0716	61.43	0.425	75.97	1.55	0.615	0.75	0.49
Handak	0.0972	62.064	0.426	75.92	2.21	0.814	0.6	1.0
Sabek	0.0682	61.74	0.425	79.32	1.955	0.855	0.5	0.84
Kikou1	0.0896	61.98	0.426	74.48	1.506	0.552	0.7	1.16
Kikou2	0.0992	61.53	0.425	76.49	1.46	0.629	0.7	0.98
Kikou3	0.0764	62.834	0.425	85.11	0.941	0.448	0.7	0.99

Table 5.7. Calibration parameters selected using sensitivity analysis.

5.3.5. Method comparison

In the previous pages, we presented three infiltration methods we tested on the Beni Mellal catchments in order to find the best-suited one for our study. If we compare the results obtained before calibration by each of the three methods (Figure 5.16), the Initial and Constant Loss method appears to be the most appropriate for the four catchments, as its results are closest, in terms of peak discharge, of the field-estimated values. Calibration, performed on the basis of the sensitivity analysis presented above, brought the simulated hydrograph as close as possible to the expected peak values.

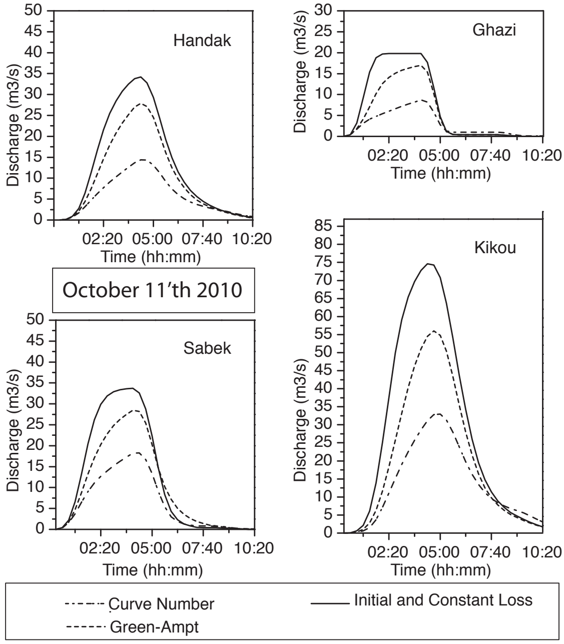


Figure 5.16. Result comparison for SCS CN, Green-Ampt, and Initial-Constant infiltration models.

We consider the Initial and Constant Loss method as the best-suited infiltration method for the studied catchments for several reasons. First, the method is very parsimonious, as it reduces catchment complexity to only two parameters and it is sensitive to antecedent moisture conditions in the catchment through the initial abstraction parameter. Second, its parameters can be deduced from catchment properties like soils and vegetation cover. Third, its parameters have moderate to low sensitivity, as opposed to the Green-Ampt method. Finally, this method is extensively used in similar environments (i.e. Australia, Mahbub & Monzur 2009) for flood design.

The Green-Ampt model could also produce outputs comparable to the expected ones. Nevertheless, this method is little applicable to semi-arid carbonaceous catchments with shallow soils because of soil conceptualisation as an infinite, homogeneous environment. Shallow boundary conditions imply to drastically reduce the values of the most sensitive parameter in order to obtain realistic output hydrographs.

5.3.6. "Calibration" results

Even though peak discharge fitting was relatively good for the Initial and Constant loss method, model infiltration parameters were tuned so that the output peak discharge approaches the field-estimated values. Finally, hydrographs were obtained for each catchment (Figure 5.17). As shown below, hydrographs have a steep shape corresponding to the flash flood typical behaviour. Several peak discharge estimates were produced for each case. They stem from different estimation sources (high water marks, splash marks collected on nearby bridges) or different parameter values (Manning friction coefficient, water surface slope). Further in Section 5.4.2, we discuss the impact of such parameters on peak discharge estimates. The "calibration" provided in this study remains therefore in the estimation domain.

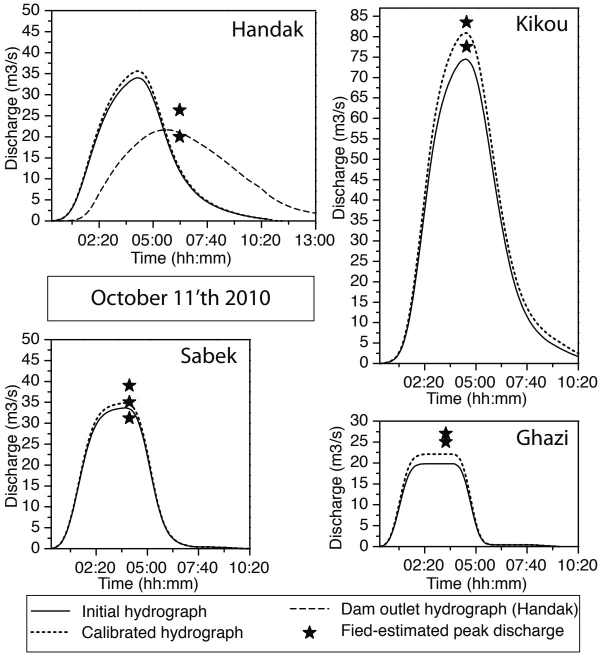


Figure 5.17. Flood hydrographs for the calibration event (11 October 2010). Several peak discharge estimations were produced using different methods (e.g. high water marks, water splash marks), or different coefficients (e.g. Manning friction coefficient, slope).

One can mention that the method underestimates flood discharge in the Aïn el Ghazi catchment, producing a very flat-topped hydrograph. We assume this situation to arise from Unit hydrograph convolution, which is hindered by the basin's very short time of concentration (50 minutes).

Photo 5-1. The Handak flood reduction dam.

For the Handak catchment, we took into account the existence of a flood-reduction dam situated at the catchment's outlet upstream of the city of Beni Mellal (Photo 5-1). This structure is part of a greater flood-mitigation strategy adopted by the local authorities. A second dam was built on the Aïn el Ghazi stream at the end of 2010 and two more similar structures were planned for the Sabek and Kikou streams (ADI 2004). The field-estimated peak discharges for the calibration event were collected downstream of the dam.

The structure was modelled in HEC-HMS as a basin retention using the elevation-storage rating function (USACE 2000). Information about dam elevation and maximum storage volume was retrieved from ADI (2004), Table 5.8.

Catchment	Storage volume	Structure elevation	Outlet characteristics (H, L,)	Dam top (H, L)
Handak	569’000 m^3	29.0 m	2 m / 1.5 m	27 m / 10 m
Aïn el Ghazi	230’000 m^3	14.7 m	2 m / 1.5 m	10 m / 5 m
Sabek	460`000 m^3	16 m	2 m / 2.3 m	-
Kikou	2’800’000 m^3	22.7 m	2 m / 3.2 m	-

Table 5.8. Flood reduction dams parameters. From ADI (2004).

5.4. Model validation

5.4.1. Validation event

To validate the model, we chose one rain event that took place on 14-15 February 2010, as flood marks and TRMM rainfall data were available. This rain event occurred during the winter-spring period when more continuous rainfall is recorded in the High Atlas. We could therefore verify if the parameter choice was applicable to different catchment wetting conditions and rainfall temporal characteristics. We notice a very good fitting in the case of the Handak stream, where the local authorities have installed a flood-reduction dam. We can also point out an underestimation of flood peak discharge in the case of the Aïn el Ghazi catchment, similar to the calibration event.

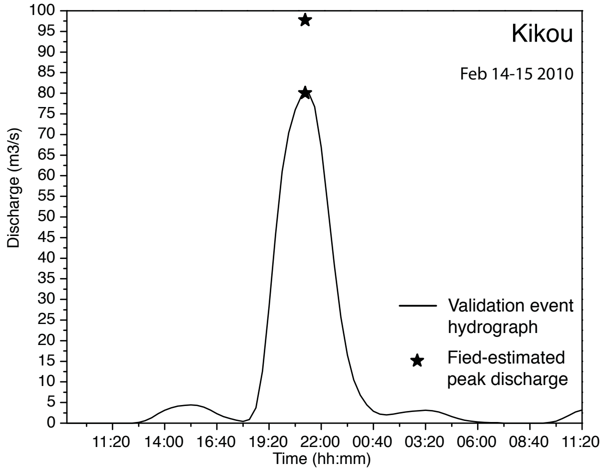


Figure 5.18. Flood hydrograph: validation event (14 -15.02.2010). Kikou.

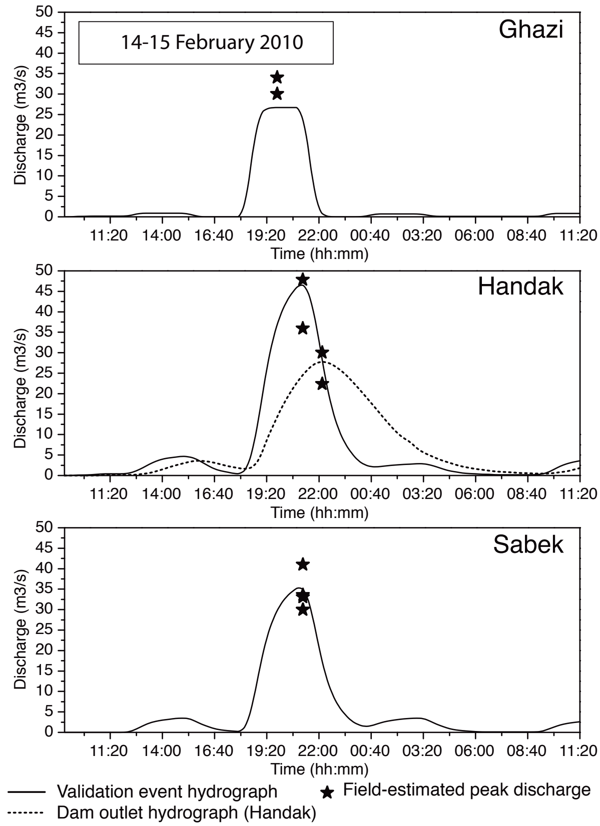


Figure 5.19. Flood hydrographs: validation event (14 -15 02 2010). Ain el Ghazi, Handak and Sabek. Handak: impact of the flood-reducing dam was accounted for; field collected peak discharge estimates upstream and downstream of the dam were produced.

This approach could offer new insights on the modelling process and its uncertainty; nevertheless, we consider it as a mere verification of our results, as we keep in mind that no real legitimacy may be attained with only two modelled events. Peak discharge comparison between modelled hydrographs and cross-section high water estimates proved to fit relatively well (Figure 5.19, Figure 5.18). All uncertainty sources considered, we judge the model capable of realistically predicting flood events for the studied catchments.

The results, in terms of peak discharge, are comparable to the estimated 10-year return period flood published by the local authorities (ADI, ABHOER 2006). We consider that the Catchment Agency study underestimates the catchment flood behaviour for several possible reasons:

- **methodology choice** (the agency used the SCS CN method that tends to overestimate infiltration, as shown in our study);
- daily **rainfall data series** up to the year 2000 were used for the statistical data

processing while floods became important after 2000; the study has therefore omitted the statistical relevance of the last decade;

- the Mediterranean mountain regions are characterized by **strong non-linearity of the hydrologic response** (Hooke 2006, Latron et al. 2009) related to great temporal and spatial variation in precipitations and contrasted seasonality, which lead to inherent difficulties to obtain reliable statistical relationships and, therefore, to correctly estimate given return period events.

5.4.2. Dealing with uncertainty

Uncertainty is intrinsic to the modelling process. It can be related to data, to the model, or to the modelled process. We explored its different facets in order to have a clearer view on how much confidence we should grant the model and the input data for the final practical purpose of mapping hazards related to floods in the city of Beni Mellal. Several uncertainty sources related to the hydrological modelling were identified: rainfall data, model parameters, and calibration methodology. Below, we discuss them and the possible ways to deal with.

Input **rainfall data** was provided by the TRMM mission, which was originally designed for regional tropical rainfall pattern studies. Therefore, its estimates might be biased by the scale parameter. We could verify this issue in the field, where one of the three reference events could not be corroborated with TRMM data. This event, that took place on 29 September 2009, produced intensive flooding in the city of Beni Mellal but was probably of very localized scale in time and space as it occurred at the end of the dry season. When modelling floods, two types of errors can result from satellite precipitation data (Nikolopoulos et al 2010): errors in the structure of satellite estimates, meaning that satellites do not account for precipitation spatial-temporal variability, and propagation of the rainfall error in the hydrological model, resulting in erroneous flood hydrographs. The lack of measured rainfall data in the studied catchments, as well as the important dissimilarity of hydro-meteorological behaviour between the High Atlas and the Tadla plain, made verifications relatively difficult.

Rainfall data could be compared to the land weather stations data from Beni Mellal and Kasba Tadla, even though both stations are situated on the outskirts of the mountainous area. Good correlations could be found for the two events reproduced in the model, but no precipitation was recorded for the 29 September 2009 event, which confirms that the latter may have had a very localized character, probably related to a small-scale convective cell in the uphill area. The Beni Mellal station recorded “stormy weather”, that could confirm our assumptions.

Model uncertainty is also related to **parameter choice** and to the degree of simplification model structure operates on the modelled process. Parameter sensitivity can account for inner model uncertainty in that it clarifies parameters role in model output variation. However, this method does not provide uncertainty quantification, but it delivers good insights in the model functioning and emphasizes the role of each parameter for the overall result.

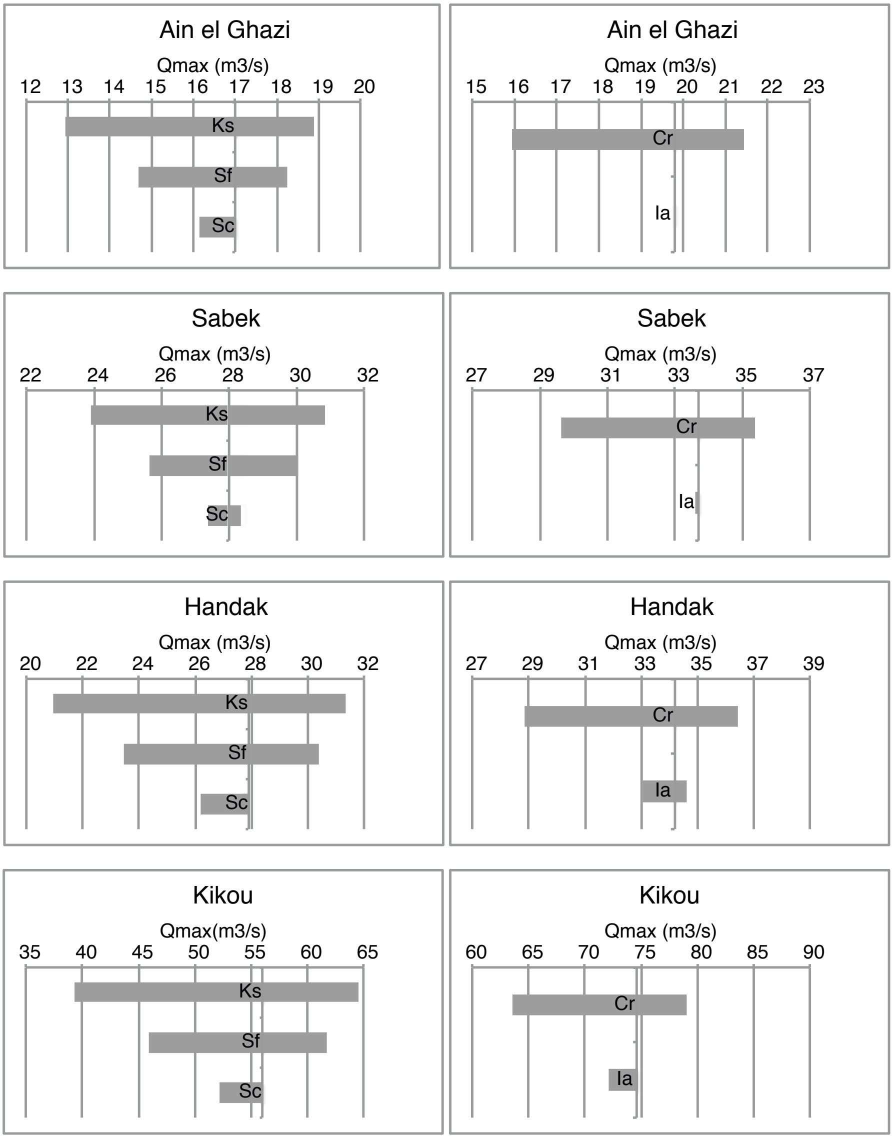


Figure 5.20. Tornado diagrams for the Geen Ampt (left) and Initial and Constant (right) loss methods. Green Ampt parameters: Ks = saturated conductivity; Sf = capillary suction front; Sc = soil saturated content. Initial and constant loss parameters: Cr = constant loss rate; Ia = initial abstraction.

We presented in this section the OFAT technique as a means of comprehending a model's behaviour through its parameters. More global sensitivity analysis techniques emerged of the need to quantify model uncertainty. Variance-based models (Hornberger & Spear 1981, Saltelli et al. 2004) depict input parameter values and resulting output uncertainty as probability distributions. Beven & Binley (1992) recognized that different sets of parameter values could play equivalent roles in terms of model output. Therefore, these parameter sets are considered as equally "correct" in the calibration process. Within this study, nevertheless, we consider that model parsimony related to the small parameter number, and the insufficiency of calibration data, justify the use of simpler methods such as OFAT. Thus, more complex analysis that would aim at quantifying model uncertainty is not justified by the available data.

We present in Figure 5.20 the results of the OFAT method in a graphical way. The tornado diagrams (Eschenbach 1992), issued from economical risk studies allow us to represent graphically parameter sensitivity in a simple way, adapted to decision-making (Figure 5.20). They depict each parameter's sensitivity in terms of output change. The output variable selected was peak discharge, with respect to its strong significance in terms of hazard. One can notice that parameter sensitivity patterns remain constant for each method. The comparison could nevertheless not extend further than the visual mode, as the tornado diagrams are unit-sensitive. For decision-making, this diagram informs in a glimpse about each parameter's weight in model functioning and helps choosing the most sensitive for better model-to-reality fitting. OFAT accounts only for the role of disparate parameters on the overall result, with no possibility of depicting parameter interactions. At the same time, it does not quantify uncertainty: it merely depicts it. Nevertheless, OFAT is very helpful in decision-making and provides a good alternative to more complex uncertainty analysis techniques when few data is available.

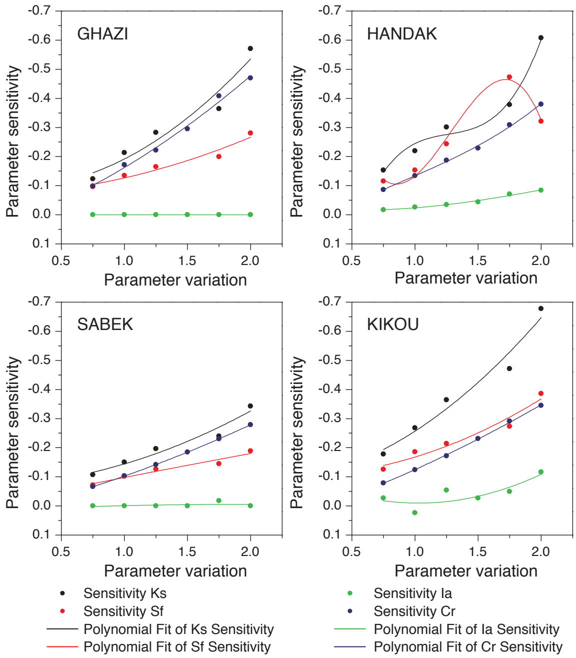


Figure 5.21. Parameter sensitivity quantification. Ks = saturated conductivity; Sf = capillary suction front; Cr = constant loss rate; Ia = initial abstraction

We attempted though to quantify parameter sensitivity in order to compare the efficiency of the methods used. We chose a simple quantification method that is unit-insensitive as it is based on the rate of change (McCuen 2003):

$$S = \frac{\delta O}{\delta P} \tag{5.21}$$

Where $\delta 0$ = output rate of change, δP = parameter rate of change, S = sensitivity.

The results of this analysis are presented in Figure 5.21. Individual sensitivity values and the corresponding polynomial fitting curves show that Green Ampt parameters are relatively more sensitive in terms of peak discharge output. The Constant rate loss parameter is also relatively sensitive, but its resulting values are more contrasting among catchments. That is, the larger the catchment is, the less sensitive this parameter becomes. We can conclude that the Initial and Constant loss method is more robust than the Green-Ampt method but we have to account for the different sources of uncertainty related to the model.

Finally, we also addressed uncertainty related to the **calibration method** (Figure 5.23, Figure 5.23). As stated above, no measured data is available for the calibration; we estimated peak discharges according to field high water markers. The accuracy of these estimates may be biased by at least two factors.

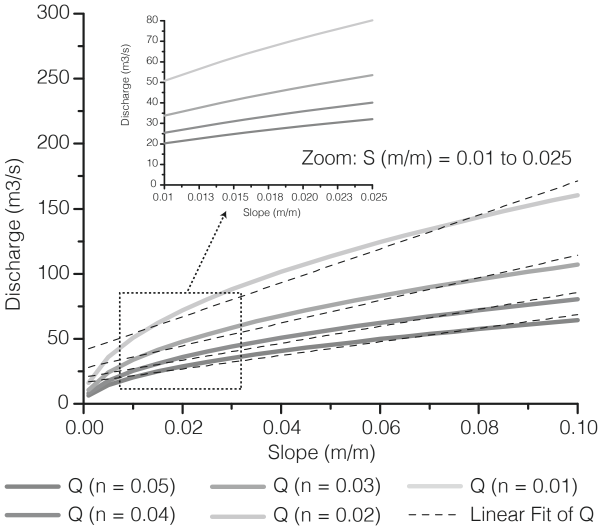


Figure 5.22. The role of roughness coefficient in peak discharge estimation.

First, **high water mark interpretation** is related to the field situation (e.g. grassland), the time passed between flood and data collection and the geomorphologist's knowledge. Therefore several information sources are required for validating these estimates. For example, high water marks may be corroborated with splash marks on bridges close to the studied cross-section.

Second, wetted section data collection may be hampered by some **parameter choice**. We consider here the effect two parameters difficult to estimate in the field have on the final peak discharge estimation for a trapezoidal cross-section on the Handak river: the water surface slope and the Manning's roughness coefficient (Figure 5.22, Figure 5.23).

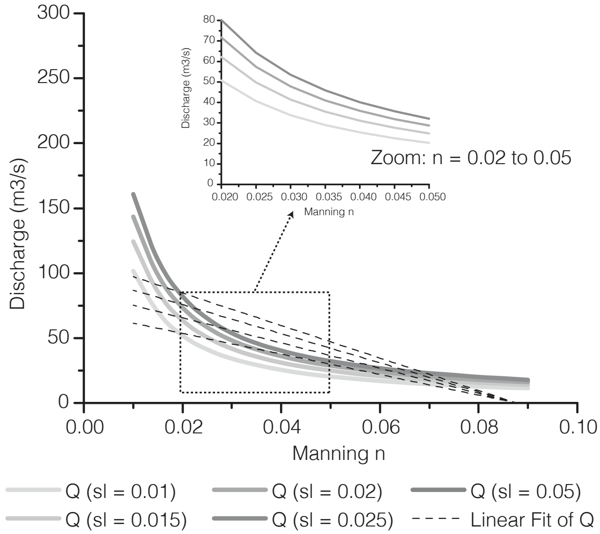


Figure 5.23. The role of water slope parameter in peak discharge estimation.

The graphs show linear correlation between these two parameters and the estimated peak discharge. As expected, higher roughness values imply smaller discharge and inversely steeper water surface slopes are related to higher discharge values. The smaller graphs highlight Manning's formula results for values of slope and roughness actually present in the study area. They suggest that for a given flood situation, peak discharge estimates may be extremely variable depending on the parameter choice. We can, thus, validate the results by only taking into account possible value intervals, not absolute numbers.

5.4.3. "Validation" criterion

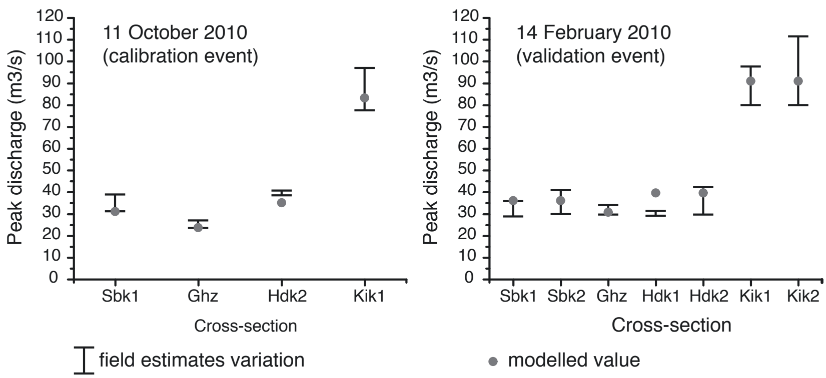


Figure 5.24. Modelled *versus* field estimated peak discharge.

Figure 5.24 shows modelled peak discharges for the calibration and validation events (14 February 2010, 11 October 2010) and the corresponding field-estimated valid intervals. The calibrated model parameters applied to the validation event show good fitting as the peak discharge values could be corroborated with field-collected flood marks. As stated above, peak discharge value ranges rather than unique validation criteria were used. All sources of uncertainty considered, we expect this model to be applicable to other rain events for the four studied catchments.

5.5. Model extrapolation

Through the hydrological modelling of two known events we attempted to realistically depict flood behaviour for the four catchments that drain the city of Beni Mellal. Their flash-flood prone character has been well represented by the modelled hydrographs. We assume even shorter events may take place in the region, but the 3-hour initial rainfall intensity data could not account for. In terms of hazard, we consider the 3-hour floods to be sufficiently accurate, as early warning or interventions are hindered by such short flood times.

This work's finality consists in bringing up a hazard map as well as a hazard mapping method applicable to environments similar to the Beni Mellal case. For hazard mapping needs, given flood return times need to be modelled. To do so, we used rectangular design storms derived from the Beni Mellal meteorological station IFD curves (Section 5.2.3). Design hyetographs were obtained for the recurrence times set to 20, 50, and 100 years and for a duration equal to each catchment's time of concentration T_c. Then, flood model was performed using the methods tested on real flood events. The results of hydrological modelling, in the shape of flood hydrographs corresponding to storms of set recurrence periods, are to be integrated to a hydraulic model at the urban level of the city of Beni Mellal.

A statistical rainfall model was established by the ABHOER (ADI 2004), using daily maximum rainfall values from 5 rain gauges located on a 50 km radius area around the study site (Beni Mellal, Aït Ouchen, Mechra Edahk, Mly Bouzekri and Taghzirt). IFD curves from the Beni Mellal meteorological station were used for the statistical adjustment as the rain data time step largely exceeds the storm duration likely to occur on the studied sites.

	AÏN EL GHAZI		HANDAK		SABEK		KIKOU	
Q_{max} / T_R	ABHOER m^3/s	This study m^3/s	ABHOER m^3/s	This study m^3/s	ABHOER m^3/s	This study m^3/s	ABHOER m^3/s	This study m^3/s
100-year	107.3	124.1	121.0	151.4	155.0	166.9	247.0	322.1
50-year	81.9	108	89.0	132.2	120.4	145.8	194.1	281.5
20-year	50.9	86	56.9	105.5	75.9	116.9	126.1	223.1

Table 5.9. Flood peak discharge comparison: ABHOER and this study: Q_{max} = estimated peak discharge; T_R = return period.

The ABHOER used the rectangular design hyetograph of $3T_c$ duration to obtain 10, 20, 50 and 100-year return time rainfall hyetographs. Rainfall-runoff modelling was then applied using the SCS Curve Number method in order to obtain runoff values for set recurrence periods of 10, 20 50 and 100 years (ADI, ABHOER 2006). Local authorities used this study's findings within the adopted flood hazard mitigation strategy.

We integrated to the model the local authorities' flood mitigation scheme based on flood reduction dams. Two of these structures are actually built; the other two are still a project. Generally, flood peaks are higher than the ones predicted by the local authorities' study: 100-year recurrence times calculated by the Agency correspond to 50-year recurrence times as obtained by our calculations (Table 5.9). Therefore, in our simulations, flood reduction dams show very little efficiency when confronted to the lowest frequency-highest intensity event of our calculations (Figure 5.25 to Figure 5.28). One can notice on the flood hydrographs that the 100-year event is not reduced by the existing structures on the Handak and Ain el Ghazi streams (Figure 5.25 and Figure 5.26). Moreover, flood hydrograph peak becomes sharper, which, in terms of hazard, signifies inducing a flash flood-like event.

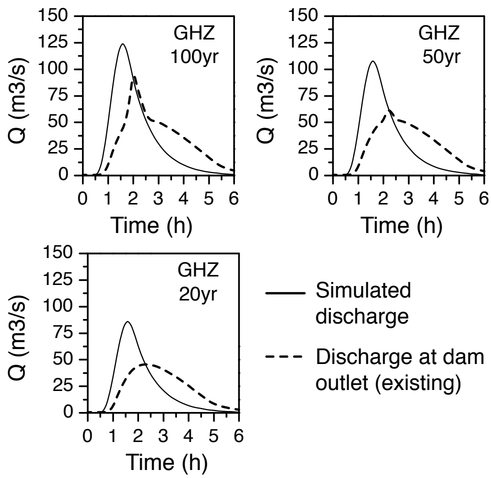


Figure 5.25. 100, 50 and 20-year rainfall recurrence floods Aïn el Ghazi catchment.

We also noticed that the modelled events that took place in February and October 2010 were comparable, in terms of peak discharge, to the 10-year recurrence event as calculated by the local authorities. This suggests again that the results obtained by the local authorities may represent an underestimation of the flood intensity related to given rainfall frequencies.

The important uncertainties underlined in Section 5.4 do not allow this study to reject the local authorities results: indeed, the estimated peak discharge values integrate the variability range of our estimations. Nevertheless, from a risk mitigation point of view, we suggest that potential underestimation of peak discharges may have important consequences when flood hydrograph assessment is aimed at dimensioning flood protection structures.

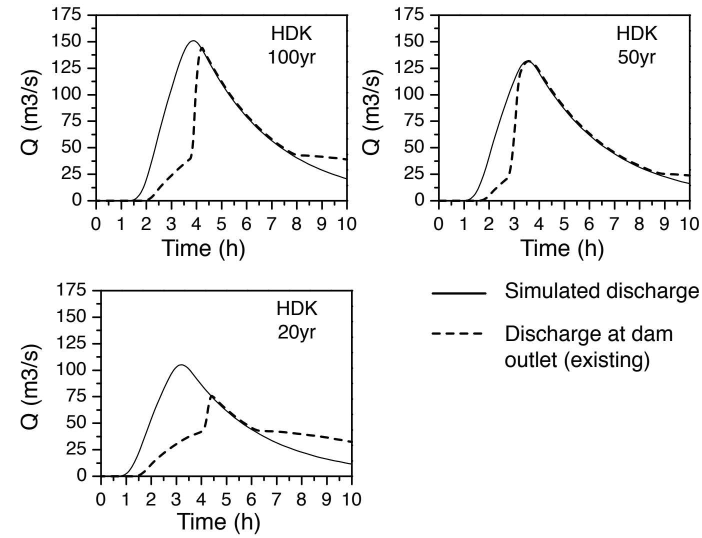


Figure 5.26. 100, 50 and 20-year rainfall recurrence floods for Handak catchment.

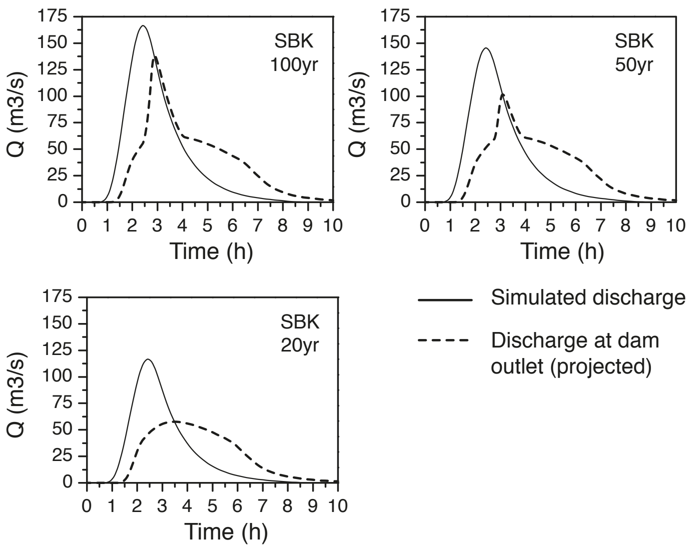


Figure 5.27. 100, 50 and 20-year rainfall recurrence floods for Sabek catchment.

We suggest that the difference of results between our study and the local authorities' is mainly related to model choice. The authorities used The SCS CN methodology to model floods for the entire Beni Mellal province. This method is extensively used in practice, even if, as we pointed out in section 5.3.4 it tends to underestimate flood peaks. We suggested that the underestimation may be related to the SCS assumption that infiltration rate is dependant on rainfall rate (Hjelmfelt 1980). Indeed, the SCS CN methodology may not be appropriate for semi-arid, quasi-impervious catchments with flash flood behaviour.

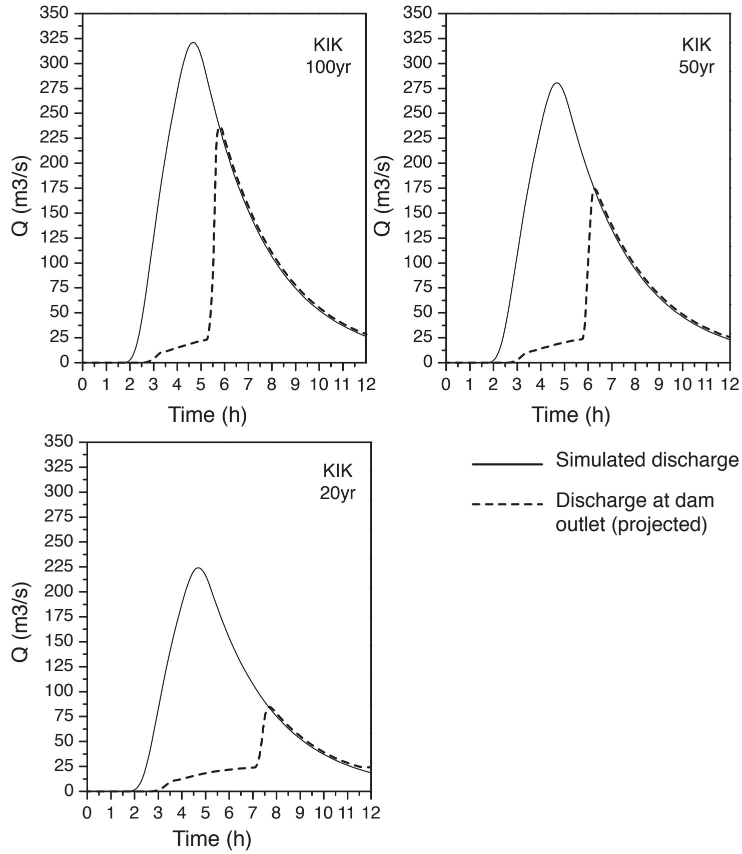


Figure 5.28. 100, 50 and 20-year rainfall recurrence floods for Kikou catchment.

We stated in Section 5.2.3 that rectangular design storms based on IFD curves tend to underestimate flood intensities by the smoothing effect operated on rainfall rate that stays constant throughout rainfall duration. We took this into account as a part of model uncertainty as well as the fact that the used model could only recreate floods issued from rainfall intensities of a given frequency and not given return period floods (Section 5.2.3). Finally, IFD curves used for storm design originate from measurements taken at the Beni Mellal meteorological station, situated at the outskirts of the studied catchments. We acknowledge the possibility that the frequencies recorded at this station may differ from conditions in the uphill area. At the same time, no other reliable information was available. Therefore, we consider these data to be applicable to out study site.

All sources of uncertainty considered, the results obtained by this study represent flood event scenarios that stem in good catchment characteristics knowledge, field-verified data and comprehensive methodology choice.

5.6. Discussion and conclusion

Hydrologic modelling represents a necessary step in hazard evaluation and subsequent mapping. This section's objective was to comprehend hydrologic behaviour of the four catchments that drain the city of Beni Mellal and to come up with flood hydrographs that would characterize flood events of 20, 50, and 100-year recurrence periods: three scenarios that cover the range of frequency-intensity relationships usually considered in flood hazard mitigation practice.

Specific knowledge of the catchments' hydrologic behaviour was gathered through the simulation of two known reference events. Hydro-geomorphologic methods of post-flood markers collection made possible the estimation of peak discharge for each catchment during the surveyed events. Therefore, partial calibration and model verification were possible in these ungauged catchments. Model fitting and validation allowed us to simulate flood events related to design storms of 20, 50, and 100-year return periods. This study's findings were compared to the ones obtained by a flood mitigation study the local authorities implemented in 2004 (ADI 2004). The existing flood mitigation structures built on the basis of the 2004 study and their role in flood hazard reduction was also assessed. Our results show higher intensity floods for similar rainfall return periods. In this context, flood mitigation structures were found to be ineffective for extreme events (i.e. 100-year return period).

The flood events we simulated by model extrapolation to given rainfall return periods are not likely to correspond to flood return periods as rainfall and flood frequencies do not necessarily match. From this point of view, our objective was only partially attained. Nevertheless, in absence of measured flood discharge data, no flood return periods could possibly be established.

In this study, we endeavour to perform flood hazard assessment in four semi-arid catchments with scarce meteorological and hydrological data. We suggest that good knowledge of catchment soil and land cover conditions and better flood understanding through post-flood campaigns is mandatory for compensating the lack of data and therefore reducing model uncertainty. In this respect, results obtained by the combination of hydrologic and hydro-geomorphologic methodologies better depict catchment hydrological behaviour. However, this approach requires interdisciplinary skills and a better involvement of geomorphologists to the hazard assessment procedures, especially in regions where scarce data hinder hydrological modelling.

As exposed in sub-chapter 5.5, there was consistent difference between the results we obtained and those that form the basis of the flood mitigation strategy actually in progress in the city of Beni Mellal. Several findings suggest that the local authorities underestimated flood hazard related to the four catchments that drain the city. We suggest that our results respect the precautionary principle that requires considering worst-case scenarios. In this respect, by improved methodology choice, we can compensate for the smoothing effects of simplified design storms, and for uncertainties related to unknown catchment moisture conditions or model simplification of the reality.

Throughout this procedure, we aimed at obtaining flood hydrographs typical of given reference events. The results achieved in this section form the entries of a hydraulic model that is expected to assess hazard intensity and frequency in the urbanized perimeter of Beni Mellal. The hydraulic modelling process is presented in the next section.

6. Hydraulic flood modelling

6.1. Introduction

Flood hazard mapping and subsequent mitigation procedures require hazard to be assessed in a quantitative manner in order to adapt mitigation objectives to hazard magnitude and community exposure. Flood hazard assessment requires describing flow characteristics for a given region. One may distinguish between hydrological flow, which is a function of external factors (e.g. slope or roughness), and hydraulic flow that depends on internal parameters such as the water surface. From a practical point of view, hydrological models provide flood hydrographs that allow assessment of flood event magnitude in terms of flood discharge, timing and frequency. Hydraulic models on the other hand depict flood routing and inundation characteristics within the hazard-exposed areas. For flood hazard mapping purposes, hydraulic models provide the necessary hazard quantification of flood extent and intensity (i.e. water depth and water velocity) for given flood recurrence periods.

The objective of this chapter is to model flood inundation for events with recurrence periods of 20, 50 and 100 years for the four streams that drain the city of Beni Mellal. We produce maps of flood depth, velocity and inundation extent for the set return periods in order to describe hazard related to these events at the urban level. We choose the best-suited model to depict flood hazard in this specific flash flood-prone piedmont region by achieving a compromise between available data, actual flood hazard mapping needs and the cost-effectiveness of methods.

This chapter first sets the theoretical framework necessary to address floods from a hydraulic point of view. We then test two hydraulic models by simulating one field-monitored event (11 October 2010) and we choose the best suited one according to this chapter's objectives and the available data. We then address model validation according to field-collected verification data (i.e. flood extents) to extrapolate the model to the return periods of 20, 50, and 100 years.

6.2. Theoretical framework: hydraulic models

6.2.1. Hydraulics: flows and floods

Flow definitions

Flood modelling is based on fluid mechanics concepts for free-surface flow (French 1985). Fluid flow can be classified according to several flow characteristics like depth and velocity, or fluid characteristics like viscosity or density.

Whether flow depth is stable or it varies in time, flow will be considered as **steady** or **unsteady** respectively. If depth is stable or it varies with distance, flow is considered to be **uniform** or **non-uniform** respectively. Flow uniformity implies a steady state (Table 6.1).

Flow type	Rule	Flow type	Rule
Steady	$\boldsymbol{\partial y / \partial t = 0}$	Uniform	$\boldsymbol{\partial y / \partial x = 0}$
Unsteady	$\boldsymbol{\partial y / \partial t \neq 0}$	Non-uniform	$\boldsymbol{\partial y / \partial x \neq 0}$

Table 6.1. Flow classification according to its variation in time ($\boldsymbol{\partial t}$) and in space ($\boldsymbol{\partial x}$, $\boldsymbol{\partial y}$).

The ratio of flow velocity (inertial forces) and internal fluid viscous forces classifies flow as **laminar**, **transitional** or **turbulent** according to the Reynolds number (Table 6.2), where U = average velocity, L = characteristic length, and v =kinematic viscosity:

$$R = \frac{U * L}{v} \tag{6.1}$$

Flow type	Rule
Laminar	$\boldsymbol{R \leq 500}$
Transitional	$\boldsymbol{500 \leq R \leq 12500}$
Turbulent	$\boldsymbol{R \geq 12500}$

Table 6.2. Flow classification using the Reynolds number.

Flow in natural streams is by definition turbulent a it is generally superior to 12500. Flow velocity in turbulent flows is conceptualized as the sum of an averaged velocity in the x, y, z directions respectively, and a random, turbulence related component:

$$\begin{aligned} u &= \bar{u} + u' \\ v &= \bar{v} + v' \\ w &= \bar{w} + w' \end{aligned} \tag{6.2}$$

Where u, v, w = flow velocity in the x, y and z direction respectively; $\bar{u}$, $\bar{v}$, $\bar{w}$ = averaged velocity in the x, y and z direction respectively; u', v', w' = turbulent velocity in the x, y and z direction respectively.

The ratio of flow velocity U (inertial forces) and gravity classifies flow as **subcritical**, **critical** or **supercritical** according to the Froude number F (Table 6.3), where g = gravity acceleration and the characteristic length L is related to the flow area or the water depth:

$$F = \frac{U}{\sqrt{g * L}} \tag{6.3}$$

Flow type	Rule
Subcritical	$\boldsymbol{F < 1}$
Critical	$\boldsymbol{F = 1}$
Supercritical	$\boldsymbol{F > 1}$

Table 6.3. Flow classification using the Froude number.

Subcritical flow is gravity-dominated while supercritical flow is inertia-dominated. The transition from one state to the other, also called a hydraulic jump, is abrupt and therefore triggers high flow turbulence and energy dissipation (French 1985, Zhou & Stansby 1999). In flood modelling, this process may imply numerical shocks related to the hydraulic jump. Different solutions for capturing the hydraulic jump were found and will be discussed further in this chapter.

Free surface flow governing equations

Flow must be consistent with conservation laws that generally state "the total magnitude of a certain physical property of a system such as mass, energy or charge remains unchanged" (Oxford dictionary of physics 2009). Governing equations for free-surface flow are the mass and momentum and energy conservation laws. Flow is by definition 3-dimensional; therefore, in a Cartesian system of coordinates, the law for the conservation of mass (continuity equation) is written using time-averaged velocities u, v, and w in the x, y, and respectively z direction:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{6.4}$$

To account for turbulence, the random velocity components in equation (6.2) are integrated:

$$\frac{\partial(u+u'\ )}{\partial x}+\frac{\partial(v+v'\ )}{\partial y}+\frac{\partial(\ w+w'\ )}{\partial z}=0 \tag{6.5}$$

The momentum given by the product of mass and velocity defines fluid motion. The momentum conservation law states that the change in a system's momentum is equal to the total forces acting on the system. In incompressible fluids, the law is written according to the Navier-Stokes equations. In a Cartesian system and for turbulent flows, these equations can be written using the Reynolds formulation (French 1985, Lane 1998) for the x, y, and z directions:

$$\begin{gathered}
\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)\\
=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)-\rho\left(\frac{\partial u'^2}{\partial x}+\frac{\partial u'v'}{\partial y}+\frac{\partial u'w'}{\partial z}\right)\\
\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)\\
=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)-\rho\left(\frac{\partial u'v'}{\partial x}+\frac{\partial v'^2}{\partial y}+\frac{\partial v'w'}{\partial z}\right)\\
\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)\\
=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)-\rho\left(\frac{\partial u'w'}{\partial x}+\frac{\partial v'w'}{\partial y}+\frac{\partial w'^2}{\partial z}\right)
\end{gathered} \tag{6.6}$$

where ρ = fluid density, p = pressure, μ = fluid viscosity.

Eddy viscosity

Given their random character, the turbulent components apparent in equations (5.5) and (5.6) create a difficult problem for solution closure (Lane 1998). In the mass conservation law, the random components are usually omitted when using the equation for practical purposes (French 1985). In the momentum equation, an often-used approach consists in using the Boussinesq assumption, which states that shear stresses related to turbulence are proportional to the mean rates of strain (Lane 1998), by an **eddy viscosity** coefficient ϵ:

$$-\overline{u'v'} = \epsilon\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) \tag{6.7}$$

Molecular viscosity is regarded as a property of the fluid, whereas eddy viscosity is a property of flow and therefore cannot be a constant (French 1985, Olson and Wright (1990) cited in Lane 1998). The formulation used to express eddy viscosity may strongly influence flow modelling through the way it actually accounts for turbulence. Issues like modelling the hydraulic jump in hydraulic structures or correctly accounting for turbulence in flood overflow processes are at the heart of the eddy viscosity formulation choice.

6.2.2. Hydraulic model typology

Flow is, as stated above, 3-dimensional, generally turbulent and unsteady. Depending on slope, roughness or channel configuration, flow passes from critical to subcritical and vice versa, allowing for turbulence and energy dissipation to occur in a rather complex way. Nevertheless, for practical applications and modelling, the governing equations of conservation of mass, momentum and energy as well as flow characteristics themselves are simplified. The simplifications depend of the model's final use, available data, allowed computational costs and the actual processes that need to be represented. The parsimony principle, presented in Chapter 6 for hydrologic models, is equally applicable in the present case. Two types of simplifications are accounted for in this chapter, as they concern hydraulic models application for the study site in Beni Mellal. We first present the difference between modelling steady or unsteady flows; then, we deal with 1- and 2-dimensional simplifications of the governing equations presented above.

Steady versus unsteady flow

The difference between steady / unsteady flow types is related to flow variability in time (Section 6.2.1, Table 6.1). Steady flow is not generally recurrent in nature, but this simplification is allowed or necessary depending on the needs and means of the model. In the case of flood hazard prediction, flood extent and intensity assessment for a given peak flow may be sufficient for short duration events such as the flash floods in Beni Mellal, as the assessed values concern the maximum magnitude of the given event. Steady flow is by definition uniform, that is, depth, flow area and velocity are constant throughout the flow reach. Thus the time component of the governing equations disappears. The continuity equation can then be written as a constant value

$$Q = u_1 A_1 = u_2 A_2 = u_n A_n \tag{6.8}$$

Where Q= discharge, u = velocity and A = wetted section. The transferred momentum for a steady flow during a given time period Δt is written as:

$$F = \frac{\rho_2 A_2 u_2 \Delta t u_2 - \rho_1 A_1 u_1 \Delta t u_1}{\Delta t} \tag{6.9}$$

Where F = force or momentum, ρ = fluid density, Δt = flow duration in time.

By introducing the discharge formulation from equation (6.8), and assuming that the fluid has a constant density ρ, the transfer of momentum becomes:

$$F = Q\rho(u_2 - u_1) \tag{6.10}$$

As flow velocity can be approximated knowing channel friction and water surface slope, empirical or semi-empirical relations like the Chezy equation or the Manning equation written below describe momentum transfer in steady flow as:

$$Q = \frac{1}{n} A R^{2/3} \sqrt{S} \tag{6.11}$$

Therefore, flow velocity is written as:

$$u = \frac{1}{n} R^{2/3} \sqrt{S} \tag{6.12}$$

Where n = Manning roughness coefficient, R = hydraulic radius and S = slope. Roughness coefficients may be purely empirical (Manning) or have a physical assumption basis (Chezy). Yet, their estimation is crucial for model performance as they represent the main calibration features for this type of model (French 1985).

Flood waves represent typical unsteady flow phenomena. The representation of flow variation in time is necessary to flood mitigation strategies related to hazard prevention and alert as well as in rescue and evacuation planning. Unsteady flow models use the flow governing equations presented in Section 6.2.1 as they include a time component to represent flow variation. They can solve the complete continuity and momentum equations or approximations of these equations based on simplifying assumptions.

Solving the simultaneous governing equations requires setting up a numerical scheme. Explicit schemes determine unknown values or state of a system from its antecedent known values or state (Barton 2001). Implicit schemes are used when the unknown ones are given by coupled sets of equations and a matrix or an iterative technique is required for determining a solution (Hirt 2013). Even though explicit solutions are less costly in computational effort, most of the unsteady flow solutions are implicit given the great number of unknown values to be determined by the governing equations. Numerical schemes can be classified in finite-difference schemes where time and space are divided in fixed equal units or finite-element schemes where space is divided in elementary parts that best describe system conditions (Barton 2001).

Finally, upstream and downstream boundary conditions are required for setting up unsteady flow models: input flood hydrographs at the upstream end and given flow rates at the downstream boundary introduce known terms to the governing equations for solution determination.

1D versus 2D simplification

Solving the governing equations in a 3-dimensional way is computationally costly and not always justified by the practical purpose of a project; hence, the use of simplifications to the one- and two-dimensional domains.

1D models state that mass and momentum must be conserved between successive cross-sections, perpendicular to a given flow path. To compute flood depth, cross-section values are interpolated into a water surface then crossed with a Digital Terrain Model. The continuity and momentum conservation equations as written in (6.8) and (6.9) are typically one-dimensional, and they apply to successive cross-sections.

The 2D governing equations, also called Shallow Water Equations (SWE) (Balzano 1998, WBM Oceanics Autralia 2007), are used to model long-waves like floods or ocean tides (Bates & De Roo 2000, WBM Oceanics Autralia 2007). The main assumption in these simplified equations is that horizontal velocity is vertically uniform and vertical acceleration is negligible. This assumption is valid when the length of the flood wave is much larger than the water depth (WBM Oceanics Autralia 2007) as it is the case in floods. Models may solve the full equations or simplified variations of SWE. A variant of the full shallow water equations is presented in Section 6.3.2, equations (6.13) and (6.14). They allow computation of flood extent, flood depth and depth-averaged velocity at each node or cell of the 2D domain (Bates & De Roo 2000). 2D models achieve a better representation of flood processes than 1D models on unconfined surfaces like floodplains (Bates & De Roo 2000) and alluvial fans (Pelletier et al. 2005). They reduce uncertainty, as flow paths are not imposed upon the model (Syme 2006). However, 2D models are computationally intensive (Syme 2006) and less suited for parameterization (Bates and De Roo 2000).

6.2.3. Flood modelling: necessary processes

Hydraulic models are used in hazard assessment procedures according to specific needs and within the limits of specific means. Three types of requirements may orient model choice for flood hazard assessment. Depending on the desired type of assessment, the necessary outputs may be flood extent or require more flood information such as maximum water depth and velocity at a given point. The given environment may impose the use of a more simplistic or, on the contrary, more complex modelling. Finally, flood timing may be required.

Flood hazard assessment procedures require different estimates depending on flood type: slowly rising floods related to water table dynamics are best described by flood extent and depth, while fast propagating flash-floods require assessment of flow velocity. In our study case, full assessment of flood extent, water depth and flow velocity are necessary because of the flash-flood character of the events occurring here and the flow path uncertainty related to specific alluvial fan morphology.

Channelized flow representation differs in terms of modelling requirements for unconfined surface hydraulics. Topography and its influence on flow path definition, spatial variation of the roughness parameter, and the turbulent transition from channelized to unconfined flow must be assessed in order to obtain a better flood process representation. For this study site, where alluvial fan morphology directly impacts flood hydraulics, it is necessary to assess flood behaviour correctly on unconfined surfaces of alluvial fans as well as in channelized reaches. It has been proven that 1D models can correctly predict channelized flow while 2D models give a higher order representation of unconfined surface flows (Bates & De Roo 2000, Barton 2001, Tayefi et al. 2007).

Finally, some flood hazard mitigation procedures may require knowledge of how floods develop in time. For example, setting up a flood alert and / or evacuation procedure is impossible without knowing the time span allowed by a flood for such measures. In the case of hazard mapping for planning needs, assessment of flood evolution through time is not compulsory as flood hazard maps reproduce the maximum flood extents and intensities for given scenarios. Hence, steady-flow models that represent flood characteristics related to a flood peak have proven to be sufficient for representing flood hazard for a given site.

6.3. Flood inundation modelling in Beni Mellal

Model choice criteria

The purpose of this project is to produce flood hazard “intensity” and “frequency” maps that depict the maximum flood intensity for events of given recurrence periods. A hydraulic model is needed in order to assess these criteria at the study site scale. The chosen model is not necessarily time-varied; hence, a steady flow model can satisfactorily respond to the hazard map requirements. Moreover, this model needs to represent hydraulic processes sufficiently in both channelized reaches and over unconfined flow surfaces such as the alluvial fans in Beni Mellal. Finally, a practical need related to project reproducibility in developing countries requires using a cost-effective or open-source tool as for to allow the reuse of the method with low financial costs.

Criterion	HEC-RAS	TUFLOW
Spatial	1D	2D
Representation: channelized flow	Good	Poor/Good (resolution bound)
Representation: unconfined flow	Poor	Good (resolution bound)
Temporal	Steady / unsteady flow	Unsteady flow
Representation for map needs	Good	Good
Licence type	Open-source	Commercial
Cost-effectiveness	Very good	Poor

Table 6.4: HEC-RAS and TUFLOW: model choice criteria.

Two models were tested for flood hazard assessment on the Beni Mellal urban area. These are the 1D HEC-RAS steady flow model (USACE 2010) and the 2D, unsteady flow TUFLOW model (WBM Oceanics Australia 2007). In principle, each model responds partially to the evaluation criteria developed above (Table 6.4).

Indeed, channelized flow is precisely represented in 1D through successive cross-sections, while in 2D cell resolution plays an essential role in representing narrow channels. For satisfactory results, minimum 3 grid cells should represent the channel

(WBM Oceanics Australia 2007). On the other hand, 2D models prove more efficient at representing unconfined flows than 1D models (Tayefi et al. 2007), but better spatial resolution, related to better temporal resolution, is expected to increase model accuracy in that computation of the governing equations approach the continuum (Hardy et al. 1999).

The following sections present each model, the flood simulation process and a comparison of the obtained results. Finally, the best-suited model (for flood hazard assessment) is retained for flood hazard mapping in the urban area of Beni Mellal.

6.3.1. HEC-RAS: 1D, steady flow model

Model presentation

The U.S. Army Corps of Engineers developed HEC-RAS (Hydrologic Engineering Center River Analysis System) model since 1995 as a substitute for the well-established HEC-2 software that was used since 1964 in water management projects. HEC-RAS provides a 1D steady or unsteady flow computational platform (USACE 2010). The channel and flood plains are modelled in HEC-RAS as a series of cross-sections perpendicular on the flow path. The required inputs for the model are the cross-section geometry and its parameters (roughness, upstream and downstream distance, contraction and expansion ratios, etc.) and boundary conditions (upstream discharge input, downstream cross-section slope for normal depth computation). HEC-RAS also supports structure modelling such as bridges, culverts, and protection levees.

Data pre-processing

Files creation for HEC-RAS is possible in ESRI ArcMap via the HEC-GeoRAS extension. Cross-sections were designed in order to represent all areas subject to flooding as identified during field surveys. Typical of an alluvial fan flood area, the cross sections widened downstream. Particular difficulties were encountered when modelling the confluence point with Day stream, where relatively large cross-sections from different streams intersected.

For each cross-section, topographic information was extracted from a DTM obtained by contour line interpolation from the 1:2’000 urban plan of Beni Mellal. Contour line equidistance is equal to 1m and may attain 0.5m in flat areas. Setting up the DTM was relatively cumbersome as the AutoCAD format of the topographic data in the urban plan was intended for graphical use or cartographic representation only. That is, contour lines were represented by a multitude of individual segments holding erroneous altitude values that required manual merging and correct value assignment.

Moreover, stream channel geometry could not be deduced from the existing topographic data. Thus, manual geometry setting was subsequently undertaken in HEC-RAS using field collected cross-sections, sketches, and images. Manual optimization of bridges and culverts was also undertaken, as the preliminary cartographic phase of this project had emphasized the role of structures in flood development and aggravation (Chapter 4). Changes in channel geometry related to flood mitigation works up to July 2010 were taken into account. Therefore, only modifications of the Handak stream and the confluence point were accounted for by our project. Successive cross-section densification was undertaken in order to account as accurately as possible for the complex topography of the alluvial fans. Finally, cross-sections were interpolated between the initial ones to obtain a 5m distance section series. In the whole around 1000 cross-sections were created for each stream.

Land use information retrieved from the 1998 urban plan, updated using 2009 GeoEye images provided by Google Maps, formed the basis for roughness coefficient estimations at the cross-section level. Manning roughness coefficients (n) were estimated using the table method proposed by Chow (1959) where each land use class holds an expected range of values of the n parameter. For simplicity, land use classes were resumed to six types (Table 6.5).

Boundary conditions at the upstream end consisted of peak discharges estimated for the 20, 50, and 100-year return periods as obtained by hydrologic modelling in Chapter 6. Downstream boundary conditions provide a consistency condition for the model. It consisted of an input water surface slope, integrated to the Manning formula in order to obtain the normal depth, i.e. the unique depth for which a given discharge would produce uniform flow (French 1985). In order to avoid too great an impact of the downstream boundary condition on model results, additional cross-sections were created downstream of this study's area of interest. As floodwaters from Sabek, Aïn el Ghazi and Handak converge on the Day junction area, it was necessary to model flows simultaneously for these streams and therefore to find the best modelling strategy for the confluence. The Kikou floods were modelled in a separate project.

Parameter choice and boundary conditions

Roughness coefficients $\boldsymbol{n}$ were estimated according to Chow (1959) for the following land use classes (Table 6.5).

Land use class	$\boldsymbol{n}$	Land use class	$\boldsymbol{n}$
Concrete channel	0.01	Urban surface (streets)	0.02
"Clean" channel	0.03	Grassy surface	0.06
"Rough channel"	0.04	Trees, olive plantation	0.08

Table 6.5. Roughness coefficient related to six land use types.

Type	$\boldsymbol{C}$	Type	$\boldsymbol{C}$
Contraction coefficient	0.01	Expansion coefficient	0.03

Table 6.6. Contraction - expansion coefficients for supercritical flow.

Contraction / expansion coefficients are used to account for velocity head variation between successive cross-sections (USACE 2010). Contraction / expansion values were assigned to each cross-section to represent gradual transitions in supercritical flow (USACE 2010) as the fast propagating shallow floodwaters specific of the studied area are expected to have a supercritical behaviour (Table 6.6).

Boundary conditions were used to set an initial water surface necessary for the model to start calculations. Supercritical flow modelling requires setting boundary conditions at the upstream reach end (USACE 2010). We used normal depth as the boundary condition for the four reaches. Normal depth is calculated using an energy slope that can be approximated by the channel's average slope, as uniform flow states that channel bottom and energy grade are parallel (Table 6.7).

Reach	Slope (m/m)	Reach	Slope (m/m)
Sabek	0.03	Handak	0.085
Aïn el Ghazi	0.076	Kikou	0.08

Table 6.7. Upstream boundary condition for the four streams: water surface slope.

Peak discharges (m^3/s) for the field-monitored 11 October 2010 event and the 20, 50, and 100-year return periods as computed by the hydrologic model presented in Chapter 6 were entered at the upstream end of the reaches (Table 6.8). The October 2010 event was chosen as a validation event for the model as field mapped flood extents were available. Flood reduction effect of the Handak dam has been taken into account.

Reach	October 2010	20-year	50-year	100-year
Sabek	34.9	116.9	145.8	166.9
Aïn el Ghazi	22.1	86	108	124.1
Handak	35.8	76.6	131.9	151.4
Junction Sabek-Ghazi	57.0	202.9	253.8	291
Junction Sabek-Day	57.0	202.9	253.8	291
Junction Handak-Day	92.8	279.5	385.7	442.4
Kikou	81.0	224.9	281.5	322.1

Table 6.8. Peak discharges in m^3/s for the four streams modelled reaches.

6.3.2. TUFLOW: 2D, unsteady flow model

2D models, as compared to 1D models, are thought to deliver better process representation of floods occurring on areas of complex topography such as alluvial plains and fans (Bates & De Roo 2000, Pelletier et al. 2005, Tayefi et al. 2007). We tested flood simulation for the Beni Mellal urban area using the 2D, unsteady flow model TUFLOW. The model is available on the Aquaveo™ SMS (Surface-water Modelling Solution) platform. This commercial software can be tested using a trial licence. For academic use, special rates can be obtained.

Model presentation

TUFLOW has been developed since 1989 as a 1D/2D coupled model for modelling coastal and later riverine processes (Syme & Apelt 1990, Syme 2001). The 2D part of the software is a hydrodynamic model that solves the full SWE under the form:

$$\frac{\partial \zeta}{\partial t}+\frac{\partial (Hu)}{\partial x}+\frac{\partial (Hv)}{\partial y}=0 \tag{6.13}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}-\mathcal{L}_v+g\frac{\partial \zeta}{\partial x}+gu\frac{\sqrt{u^2+v^2}}{C^2H}-v\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}=F_x \tag{6.14}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}-\mathcal{L}_u+g\frac{\partial \zeta}{\partial y}+gv\frac{\sqrt{u^2+v^2}}{C^2H}-v\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}=F_y$$

where ζ = water surface level; u = depth averaged velocity in the x direction ; v = depth averaged velocity in the y direction ; h = depth of water relative to a datum; $H=h+\zeta$ = total depth; $\mathcal{L}$= Coriolis parameter ; C = Chezy friction coefficient; F= external forces (wind, pressure).

Depth-averaged velocity, water depth and flood extent, as computed by this model represent basic data for flood hazard assessment. The implemented numerical technique is the Alternate Direction Implicit (ADI) finite difference scheme by Stelling (1984), based on a fixed cell rectangular grid and fixed time-step. Model numerical stability is a function of the temporal and spatial discretization and process dynamics. The Courant number may represent a stability condition (French 1985, Syme 1990):

$$Cr=\Delta t\sqrt{\frac{gH}{\Delta x}} \tag{6.15}$$

Where Δt= time-step, g= gravity acceleration, H=water depth, and Δx grid cell size. If explicit schemes are stable at $Cr \leq 1$, larger Cr can be used for implicit schemes. Time-step choice should be based on this stability measure. For practical purpose in TUFLOW, an implicit rule states that choosing $\Delta t(s)\ =\Delta x/2$ allows model stability (WBM Oceanics Australia 2007).

Initially developed for tidal process modelling, this software has proved to offer very good solutions for riverine flooding, mainly because of its stability and robustness. In tidal flats, representation of those areas subject to alternating wetting and drying stages is essential (Balzano 1998); this situation can also occur on alluvial plains or fans with complex topography. Wetting and drying algorithms provide criteria for declaring one cell wet or dry and, therefore, for delimiting those areas that witness wetting and drying processes during floods (Balzano 1998). TUFLOW implemented a fast wetting and drying algorithm based on Stelling (1986), which is well suited for floodplain modelling (Syme 2001). This algorithm is based on the fixed-grid method, where the wet area must advance or recede on a fixed-step pattern (Balzano 1998).

As described in Section 6.2.1, solving the momentum equations requires estimating the turbulent components of flow. TUFLOW uses a Reynolds averaging turbulence model. The resulting eddy viscosity can be estimated via one constant coefficient, or as a function of cell size and local velocity according to the Smagorinsky (1963) formulation. This approach stems from atmospheric research and has been developed for approximating sub-grid processes that cannot be modelled directly. In TUFLOW, eddy viscosity is given by the relationship:

$$\mu = C_x \sqrt{A_c \left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \frac{1}{2}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2} \tag{6.16}$$

Where μ = horizontal diffusion of momentum coefficient, A_c = cell area, C_x = Smagorinsky coefficient.

Data pre-processing

Topographic data were retrieved from the contour line-interpolated DTM of the 1:2’000 urban plan of Beni Mellal. Channel geometry as represented by the HEC-RAS built cross-sections was integrated to the existing DTM in order to obtain an accurate representation of the channels and unconfined flow surfaces. The elevation data was then integrated to the Aquaveo™ SMS interface where all the TUFLOW input files were created. An elevation grid of cell size = 3 m was generated. This resolution offers a good compromise between model accuracy and necessary computational effort. Moreover, the results are suited to representation on a mid-scale map as the Beni Mellal indicative hazard map (1:15’000). Land use data were imported as a GIS file into SMS and formed the basis for roughness coefficient assignment. Manning coefficient values were kept equal to those used in HEC-RAS (Table 6.5), but the buildings were assigned n = 3.0 as to account for their flow obstructing role. This approach is widely used in hydraulics modelling to represent structures when resolution of the elevation data cannot account for them properly (Yu & Lane 2006). Hydraulic structures such as crossing culverts and bridges were not modelled but considered as full obstructions to flow (undersized structures), and as free flow channels (calibrated ones). Two projects were set up, similar to the 1D model: one project for the three streams that join in the northern city part (Sabek, Aïn el Ghazi and Handak), codenamed BM and, one project for the offset Kikou stream, codenamed KIK.

Parameters choice and boundary conditions

As discussed before, in 2D models, time-step needs to be linked to grid spatial resolution to achieve numerical stability. The other important model parameters are related to the way roughness, turbulence and wetting and drying are accounted for. The parameter values are presented in Table 6.9. Roughness coefficient values are identical to those used in the 1D model (Table 6.5).

The choice of parameter values is expected to achieve a compromise between model results accuracy, computational effort, and model stability (Table 6.9). Indeed, the model spatial resolution is essential in defining output accuracy. Model time step is necessarily linked to the grid resolution; however, the chosen value impacts not only output accuracy but also model stability (see the Courant number, equation 6.15). The wetting and drying algorithm and related parameter values impact also model stability. Indeed, on surfaces where water depth tends to 0, computational instabilities may arise; thus, a wetting and drying algorithm allows these cells to be excluded from the calculation by considering them as dry cells, by using a boundary criterion. Finally, the eddy viscosity coefficient integrates the Smagorinsky formulation for turbulence treatment (equation 6.16).

Parameter	BM	KIK	Objective
Cell size (m)	3	3	Output accuracy, computational effort
Time step (s)	1.5	1.5	Model stability, accuracy, computational effort
Wet / dry depth (m)	0.025	0.05	Model stability, accuracy
Cell side wet / dry depth (m)	0.025	0.05	Model stability, accuracy
Eddy viscosity (Smagorinsky)	0.4	0.2	Model stability, accuracy

Table 6.9. TUFLOW input parameters for the BM and KIK projects.

Boundary conditions are implemented at the two ends of the modelled domain. The upstream boundary condition consisted of flood hydrographs for the 11 October 2010 field-monitored event and the 20, 50, and 100-year return period floods as modelled in Chapter 5. The October 2010 event was chosen as a validation event for the model as field mapped flood extents were available. For the Handak stream, the flood-reducing dam influence was accounted for. Downstream boundary condition consists of a control water level as computed from channel slope.

Flood maximum extent, water depth and flow velocities were computed for the chosen reference events. These estimates form the basis for flood hazard assessment in terms of flood frequency and intensity. The 2D model results for the validation event, i.e. the 11 October 2010 flood, are presented below in comparison with the results obtained by the 1D HEC-RAS model.

6.3.3. 1D versus 2D: model choice in Beni Mellal

Result comparison

As shown by Figure 6.1 to Figure 6.3, the 2D, unsteady flow model seems to better represent flooding processes than the 1D, steady flow model.

First, the 1D model does not correctly represent topography of the wide flooding surface on the alluvial fans or of the complex confluence area situated at the junction with Day stream. The junction could hardly be represented in one dimension and still preserve the topographic detail necessary for modelling such a complex surface.

It has been proved that unconfined surface flows like those occurring on our study site are two-dimensional (Yu & Lane 2006, WBM Oceanics Australia 2007). Then, 1D models require establishing flow paths for flow conveyance, whereas on the alluvial fan flow paths are by nature uncertain. The 1D model could only represent channelized reaches flow and the Day floodplain. Even though the HEC-RAS 1D model is very cost-effective as an open source tool, its applicability in environments similar to the Beni Mellal piedmont is restricted to channel flows and well-defined floodplain reaches.

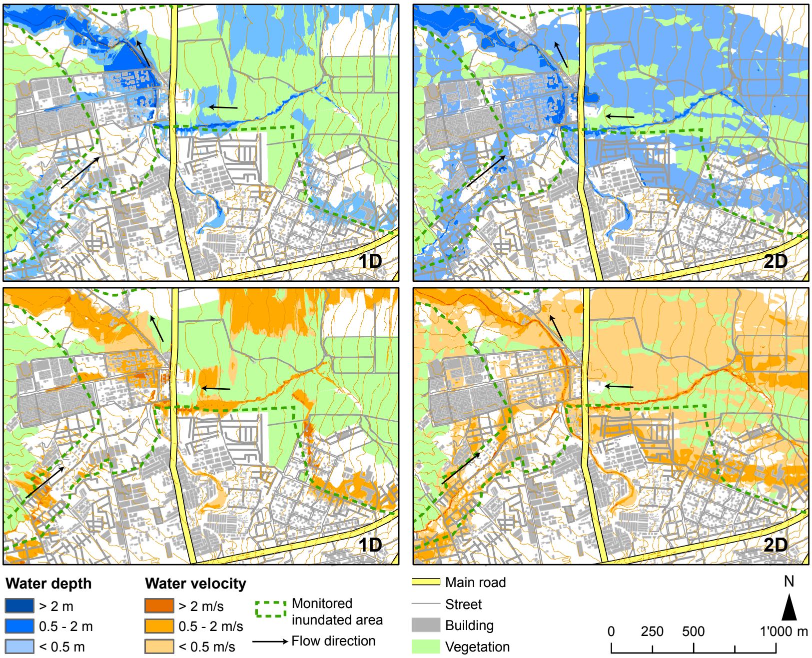


Figure 6.1. 1D / 2D result comparison. In green: monitored inundated area.

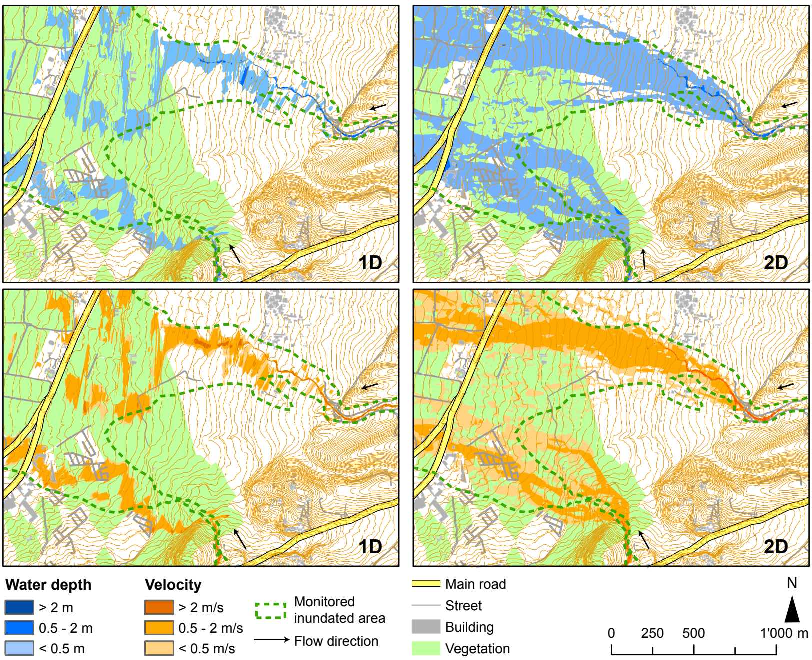


Figure 6.2. 1D / 2D result comparison on alluvial fan. In green: monitored inundated area.

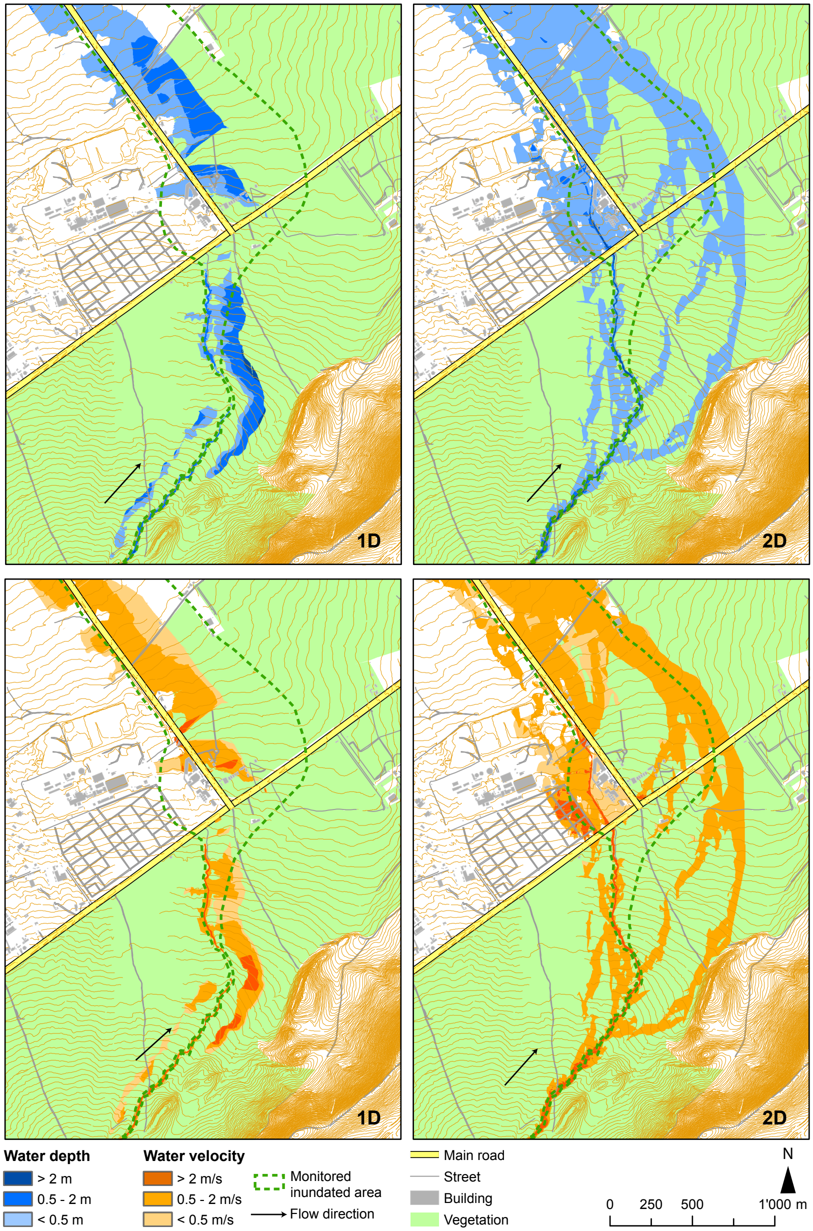


Figure 6.3. 1D / 2D result comparison: Kikou at the Marrakech road crossing. In green: monitored inundated area.

The joint project for flood hazard assessment and mapping in Fez (Lasri 2013) has successfully applied the HEC-RAS model as the valley and alluvial plain morphology of this site made it suitable to model floods as one-dimensional, steady-flow situations.

TUFLOW was not expressly developed for modelling floods on alluvial fans; indeed, this model initially developed for coastal applications was later used for river and floodplain flooding. Generally, models generated to simulate floods on alluvial fans solve simplified versions of the momentum equation such as the diffusion wave or the kinematic wave approaches (O'Brien et al. 1993, Pelletier et al. 2005). TUFLOW, on the other hand, is a full hydrodynamic model. However, the use of this model on the alluvial fan environment of this study site proved it to be appropriate for flood modelling in similar settings.

First, channelized flow was well represented relative to the grid spatial resolution and the final indicative hazard map scale of 1:15'000. To improve channel representation for more precise scales, coupling of the 2D unconfined surface domain with a 1D channel domain is possible in TUFLOW (Syme & Apelt 1990, Syme 2001).

Alluvial fan unconfined flow was well represented in the obtained results. This is a consequence of better flow-path estimation in the 2D domain as compared to the 1D model and of continuous representation of the topography and its complexity. At the fan distal area, where floodwaters from the three streams Aïn el Ghazi, Sabek and Handak meet, the 2D model effectively simulated the mixing of flows originating from different directions.

Finally, visual comparison of the results (Figure 6.1, Figure 6.2, Figure 6.3) obtained for the validation event in October 2010 and the monitored flood extents shows very good fitting for the BM project. In the KIK project, fitting was poorer; this issue is discussed further when dealing with model optimization (Section 6.3.4).

Model choice

According to the results obtained for the validation event of October 2010 and their visual comparison to the field-collected data, we consider the 2D solution to be more appropriate for flood hazard assessment on areas with alluvial fan morphology similar to our study case. TUFLOW software tested for the field site proved to represent well the flooding processes in place even though not necessarily developed for this specific environment. Regarding its cost-effectiveness, we consider this software to be relatively available even though it is commercially licenced. Indeed, a trial version of the software is available via the user-friendly, GIS-based SMS platform from Aquaveo™, and good rates are available if licensing for academic use.

The 2D unsteady flow model obtained more realistic results than the 1D model regarding flood extent and propagation on the free-flow surfaces of gently sloping alluvial fans specific to our study site. Nevertheless, dissimilarities between the field-mapped flood extents and the modelled ones suggest that model calibration could be required in order to bring the model as close as possible to reality. This is especially true for the KIK project where the modelled and mapped extents greatly differ at the main flooding point at the Marrakech road crossing (Figure 6.3). By tuning the model we might expect to obtain useful insights on the usability of the field mapping method as a verification tool for model accuracy. The next section deals with model optimization via parameter sensitivity analysis.

6.3.4. Model optimization

This chapter's objective consists of assessing hazard in terms of flood extent and intensity for the given recurrence period events of 20, 50, and 100-year that represent high, medium and low frequency reference floods as designed by the Swiss hazard assessment approach. Model validation for any of these events is unattainable as no such high magnitude event could be monitored for the study site. Therefore, model results obtained from a known event (i.e. 11 October 2010) are extrapolated to these high magnitude flood scenarios. In order to validate the known event, its accuracy regarding field-mapped data is measured. For better model comprehension, the influence of each parameter on model accuracy as well as on its capacity to correctly represent flood phenomena is assessed.

6.3.5. Model accuracy estimators

Hydraulic models performance can be assessed using measured hydrometric data like flood depth at given locations or flood discharge. When flood extent data are available, one can perform partial assessment regarding this single criterion with no possibility to assess other dynamic flood characteristics like depth or velocity. Flood extent assessment using remotely sensed data of inundation extents has been performed in several studies (e.g. Bates & De Roo 2000, Yu & Lane 2006); field-measured flood extent approaches (Tayefi et al. 2007) are less extensive as they are mainly related to geomorphic flood-hazard assessment methods (see the *Integrated Geomorphic Method* in Fernandez-Lavado et al. (2007) and Furdada et al. (2008) presented in Chapter 4). In this study we use the field-mapped flood extent as a model accuracy criterion.

	Observed			
		1=wet	2=dry	Total
Modelled	1=wet	11	12	n1+
	2=dry	21	22	n2+
	Total	n+1	n+2	n

Table 6.10. Confusion matrix: model accuracy assessment in terms of flood extent.

Several accuracy estimators are used in the literature to compare modelled flood extents to monitored ones. They are all based on a *confusion matrix* that confronts the expected classes of objects to the modelled ones. The procedure is widely used in remote sensing to assess unsupervised classifications against field-collected sample data (Stehman & Czaplewski 1998, Congalton 1991). In our case the agreement between predictions and observations is assessed at the grid cell level of the modelled area. Only two classes are to be confronted: class 1 represents the wet, flooded cells while class 2, represents those cells that remain dry during the flood event (Table 6.10).

Overall accuracy, a "naïve" measure of agreement (Rossiter 2004) is given by the ratio between the agreement cells (11, 22) and the total number of modelled cells:

$$O = 100 * \frac{\sum n_{11,22}}{n} \quad (6.17)$$

Overall accuracy may be biased by chance (it was accordingly considered as a "naïve" estimator). On the other hand, a large number of cells that remain dry during a simulation may influence its results (Yu & Lane 2006).

To dismiss the chance bias introduced by the overall accuracy, the Kappa-index (Cohen 1960), an agreement estimator originating in psychology research has been introduced first in assessing remote-sensed data classifications (Congalton 1991) and was further applied to hydraulic model accuracy assessments (Yu & Lane 2006). Indeed, this estimator takes into account the marginal totals of the confusion matrix:

$$K = 100 * \frac{n \sum_{i=1}^{2} ii - \sum_{i=1}^{2}(n_{i+} * n_{+i})}{n^2 - \sum_{i=1}^{2}(n_{i+} * n_{+i})} \quad (6.18)$$

The bias introduced by a too great number of cells that remain dry can be dismissed by calculating Kappa only for the wet cells; nevertheless the total cell number n still impacts the assessment:

$$K_1 = 100 * \frac{n_{11} - (\frac{n_{1+} * n_{+1}}{n})}{n_{1+} - (\frac{n_{1+} * n_{+1}}{n})} \quad (6.19)$$

Another estimator that has been successfully used in flood model accuracy assessments (Bates & De Roo 2000, Yu & Lane 2006) is the F measure. If used only to assess wet cells agreement, we write this measure as

$$F = 100 * \frac{\sum n_{11}}{n_{1+} + n_{+1} + n_{11}} \quad (6.20)$$

This estimator takes into account the marginal totals related to wet cells, dismissing bias for chance in this particular case; it also avoids impact of the total number of modelled cells n.

6.3.6. Accuracy estimation: results

The assessed flood extent was considered only for water depths higher than 5 cm as we think very shallow flood depths to be non-representative for the model as well as for the field collected flood data. Indeed, the model reflected typical flow path uncertainty related to gently sloping, alluvial fan morphology as a tendency to flood the entire domain at very shallow rates. 5 cm represents the threshold water depth for which a wet cell allows water to flow out of its perimeter (see Table 6.9).

On the other hand, flood depth and velocity calculation for hazard maps is based on the maximum value attained by a grid cell during the simulation instead of a peak discharge moment. Thus, very shallow water levels may have very shortly occurred on one cell without representing real hazard issues. Using only what we consider to be representative water levels allowed us to detect the flood continuity zones or flow paths related to the site's complex topography.

The model parameters as presented in section 6.3.2 were chosen to respond to model needs in terms of precision (cell size, time step) of flooding process representation (wetting and drying, turbidity) and physical environment representation (roughness). We preformed accuracy assessments using the four estimates (Overall accuracy, Kappa, conditional Kappa for wet cells and F for wet cells) on model outputs as they were produced by this initial choice of parameters (Table 6.11).

Some estimators are more easily interpreted (e.g. overall accuracy) while others remain fuzzy (e.g. Kappa); the latter should be compared to similar studies for understanding how “good” the accuracy attained actually is (Rossiter 2004). We compared our results to those obtained by similar studies (Bates & De Roo 2000, Yu & Lane 2006, Gall et al. 2007, Yu & Lane 2011). We remark our results perform less well than the best fits obtained by these authors. This situation could be partly explained by the choice to assess only representative flood depths (i.e. d > 5 cm). Some of the cited studies used accuracy assessment as a tool for calibrating model against real-life data. The range of change in accuracy related to parameter variation was very important (Yu & Lane 2006, Tayefi et al. 2007). We assume that accuracy estimators represent good markers for parameter sensitivity analysis and model optimization. On the other hand, we expect to better understand the error sources related to model relatively poor performance by tuning its parameters.

Estimator	BM project	KIK project
$\boldsymbol{O}$	66.45	59.8
$\boldsymbol{K}$	32.45	22.9
$\boldsymbol{K_1}$	30.51	38.98
$\boldsymbol{F}$	46.22	40.11

Table 6.11. Accuracy estimates obtained with TUFLOW initial parameters. O = overall accuracy; K = Kappa; K_1 = Kappa (wet cells); F = F measure.

6.3.7. Parameter influence on accuracy and flood process representation

We performed a simple OFAT analysis (see Chapter 5, Section 5.3.4 for description) by varying one parameter at one time by 0.5 and 2. The chosen parameters were: spatial resolution, roughness coefficient, eddy viscosity and additionally wetting and drying for the KIK project. The interaction between parameters has not been explored in this analysis. One should also assess the accuracy estimators in order to select the most appropriate one. We have plotted the accuracy estimators’ rate of change between simulations for each parameter in order to assess their variability (Figure 6.4). The most sensitive estimators are Kappa and conditional Kappa for wet cells that could, in both cases be greatly influenced by the total number of cells. Estimators F and overall accuracy are less sensitive: they may represent more robust markers of model overall performance. As discussed earlier in this chapter (Section 6.3.5), the overall accuracy O measure may be biased by chance while the fit measure F for wet cells eliminates the chance bias as well as the effect of the total number of cells n. F may therefore represent the best accuracy measure to use for this project. By comparing accuracy estimators’ variability per project one can suggest that the KIK project is less stable than the BM project. If the great variability induced by the roughness parameter n is present in both projects, Kikou presents comparable variations for all the other parameters (Figure 6.4, Table 6.12).

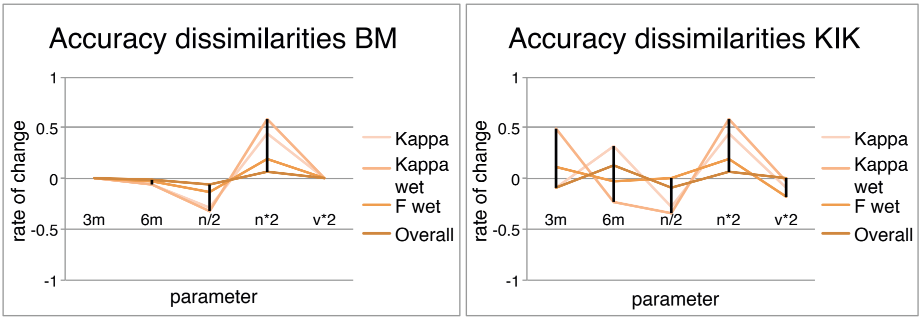


Figure 6.4. Dissimilarities between accuracy estimates for variable grid resolution, roughness coefficient and eddy viscosity coefficient.

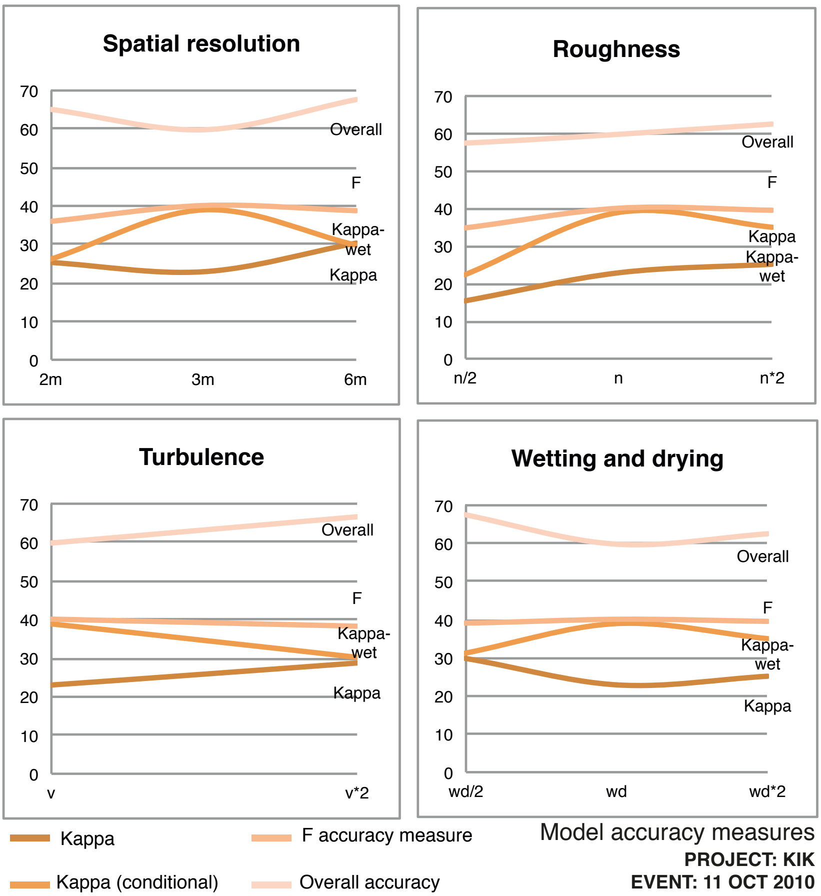


Figure 6.5. Sensitivity analysis (KIK): parameter role on accuracy estimates.

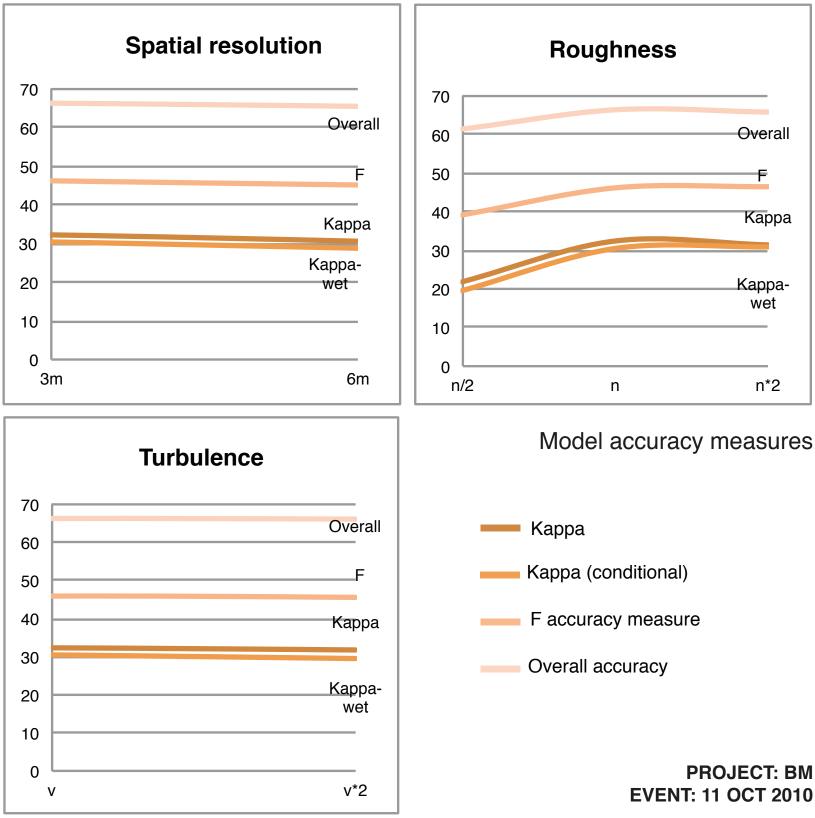


Figure 6.6. Sensitivity analysis (BM): parameter role on accuracy estimates

Spatial resolution

The cell size is believed to influence greatly the model performance, as higher spatial resolution is expected to achieve: 1) a better computational stability and flow processes representation as the space-time domain tends to the continuum; 2) a better model parameterization (Hardy et. al. 1999); 3) a better topography and structures representation and 4) higher model accuracy (Yu & Lane 2006). Yet, increasing spatial resolution by 2 means increasing the computational time by 8 in a model such as TUFLOW (WBM 2007 Oceanics Australia), as the time-step is necessarily halved in order to respect model stability rules. We suggest tuning model spatial resolution to find the best compromise between model performance and computational effort.

We tested model behaviour for spatial resolutions of 2, 3, and 6 m on the KIK project, and respectively for 3 and 6 m on the BM project. The 1 m simulations could not be completed due to model instabilities. Compared to similar studies (e.g. Hardy et al. 1999, Yu & Lane 2006), the spatial resolution we used is fairly high. Moreover, testing of TUFLOW showed that model performance is poorer with very fine grids, i.e. less than 2 m (Barton 2001). Figure 6.5 and Figure 6.6 present the behaviour of accuracy estimators when changing spatial resolution. Figure 6.5 shows that there is no significant accuracy gain in increasing spatial grid resolution; on the other hand, the 6 m model seems to perform as well as the 3 m one on the BM project (Figure 6.6) The results are summarized in Table 6.12.

We equally explored feature and flood processes representation in relation to changing spatial resolution (Figure 6.7). The 2 m model represents channels in higher detail and therefore seems to over-interpret certain topographic lows resulting in unreasonable high water ponds on the fan surface. On the other hand, flooding downstream of the main road crossing is better represented by the 2 and 6 m models. On the BM project, we focussed on how the model represents channelized flow in the urbanized Handak reach and at the confluence point on one hand and on flow representation on the "natural" alluvial fan surface at the Sabek reach on the other hand (Appendix 5). We noticed no significant difference in model representation of alluvial fan hydraulics or of the confluence point, except for poorer channel precision of the 6 m model. The urban Handak reach is less well described by the 6m model that tends to orient floodwaters towards lateral boundaries of the domain (Appendix 5). This situation could be explained by a poorer representation of channels (on this reach channels are 2-10 m wide) and an oversimplification of flow equations leading to faster flooding and therefore larger flood extent (Yu & Lane 2006).

Roughness

The roughness coefficient is the main calibration parameter in hydrodynamic models. It has been extensively used for representing structures and other floodplain topographic effects (Yu & Lane 2011). The roughness coefficient characterizes flow friction related to different surface types; therefore, it allows making the distinction between channel reaches and floodplain or free-flow surfaces. In urban environments, distinct roughness coefficients are expected to characterize structures such as roads, buildings, etc. However, the roughness parameter was proved to have smaller effects on model accuracy than spatial resolution (Hardy et al. 1999, Yu & Lane 2006). We test the influence of the roughness parameter choice on model accuracy and flood representation.

Accuracy estimators respond very similarly to the roughness parameter tuning: lower values of this parameter induce lower accuracy while increasing its values has little effects on model accuracy (Figure 6.5 and Figure 6.6). Accuracy loss due to very small friction values can be visualized on the map: indeed, the model overestimates flood extent as well as water depth (Figure 6.8). On the urban Handak reach (BM project), low friction has a similar effect to coarser grid resolution: floodwaters tend to migrate towards the modelled domain's lateral boundaries (Appendix 3). Higher friction induces lower water velocity and therefore smaller spatial spread of the flood wave. On flat surfaces nearby the Day confluence point, the high roughness effect results in water stagnation. Thus, the model fails to achieve flood connectivity between the Handak and Sabek-Aïn el Ghazi flood streams.

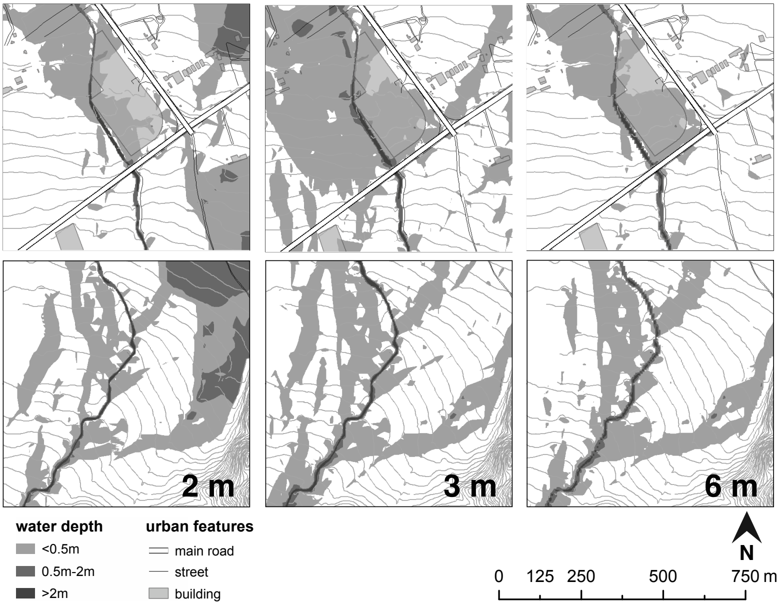


Figure 6.7. Spatial resolution and flood processes representation. KIK project

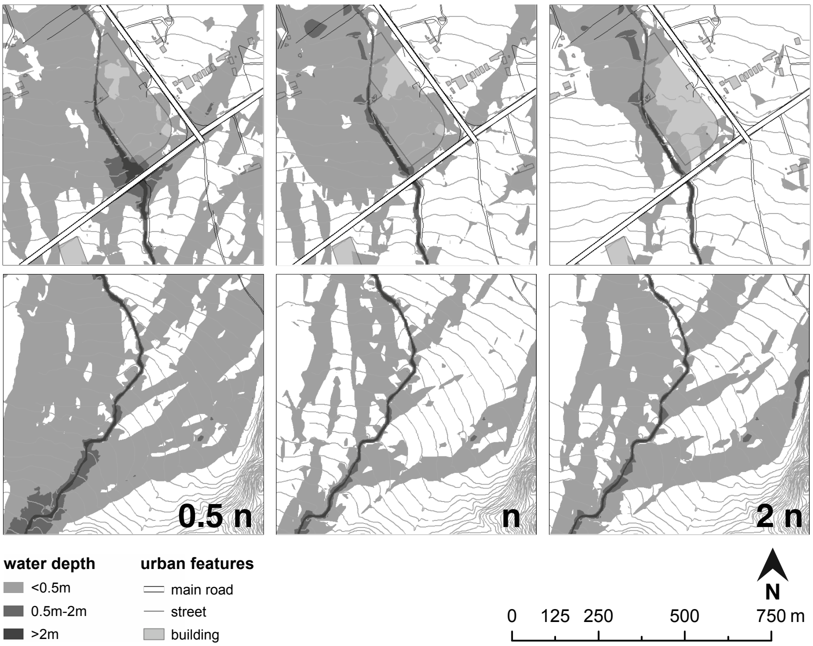


Figure 6.8. Roughness and flood processes representation. KIK project

Eddy viscosity

This parameter was introduced in order to estimate effects of representation of the turbulent components of the flow governing equations. We assess its influence on model behaviour as it has proved to be in the BM project particular case, a stability-bounding parameter. We suggest this parameter to be a "functional" or effective one (Lane 2005), i.e. a parameter that must be tuned to assure model stability. For this analysis we could only increase the parameter value as for lower eddy viscosities the model turned unstable. Model accuracy is hardly influenced by this parameter (Figure 6.5 and Figure 6.6). One can notice a relatively good representation of structures that play as obstructing effect (e.g. road embankment) (Figure 6.9). At BM, no significant change could be noticed after varying the eddy viscosity parameter (Appendix 4). However, for values smaller than 0.4, the model becomes unstable.

Wetting and drying

Wetting and drying algorithms are implemented to manage the wetting front definition for fixed-scale grids or element meshes (Balzano 1998, Yu & Lane 2006). We address in this analysis the effect of this parameter on flood extent estimation as this criterion is related to the wetting front position and implicitly to the maximum flood extent.

Accuracy estimators show dissimilarities when assessing changes introduced by the wetting and drying algorithm tuning. Kappa for instance shows better results with higher parameter values while the other estimators perform better with the initial or smaller values (Figure 6.5). This result can be related to the way the model represents flooding in the KIK project (Figure 6.10). Indeed, important flooding can be noticed upstream and downstream of the main road crossing in the Beni Mellal industrial district. This area has also been monitored as flooded even though the model could not represent it sufficiently well with the initial parameters. However, the flood extent as predicted with higher wetting and drying values is overestimated on the stream left bank. We suggest that the wetting and drying parameter, by its flood slowing effect could more accurately represent the street and culvert obstructing effects on the flood but could not precisely estimate flood extent downstream of the obstruction.

Optimization: concluding remarks

Sensitivity analysis on four determining parameters (Table 6.12 and Table 6.13) allowed us to draw several conclusions. First, it is not necessary to increase spatial resolution for the two models; the initial 3 m resolution performed well in accuracy and process representation; lowering the resolution would induce poorer channel representation. Then, lowering roughness values induces an overestimation of flood extents while too great friction values result in water ponding on flat surfaces on distal fans and Tadla plain. Therefore, the initial values offer a good compromise for the two models. Third, eddy viscosity does not significantly influence accuracy or process representation. Finally, wetting and drying parameter values seem to regulate flood extent and local water depth estimations.

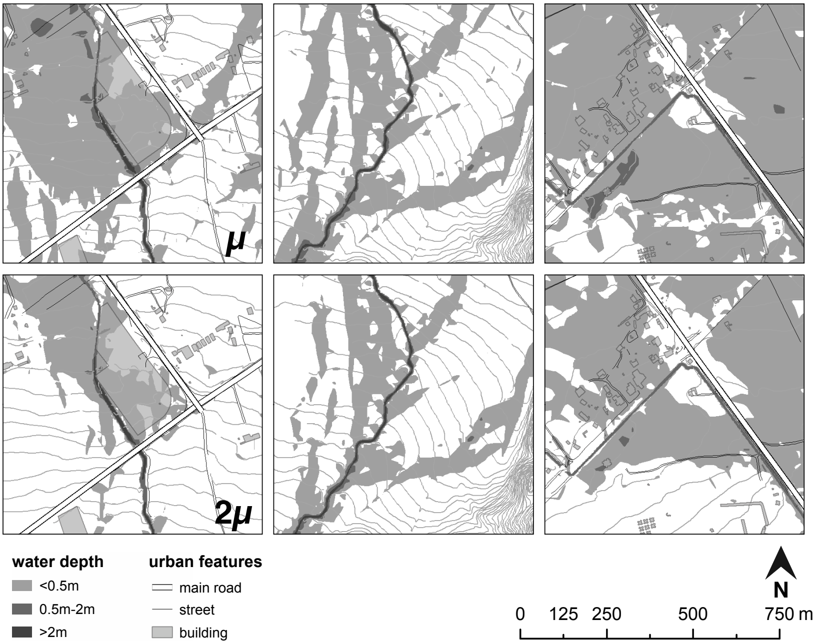


Figure 6.9. Eddy viscosity and flood processes representation. KIK project

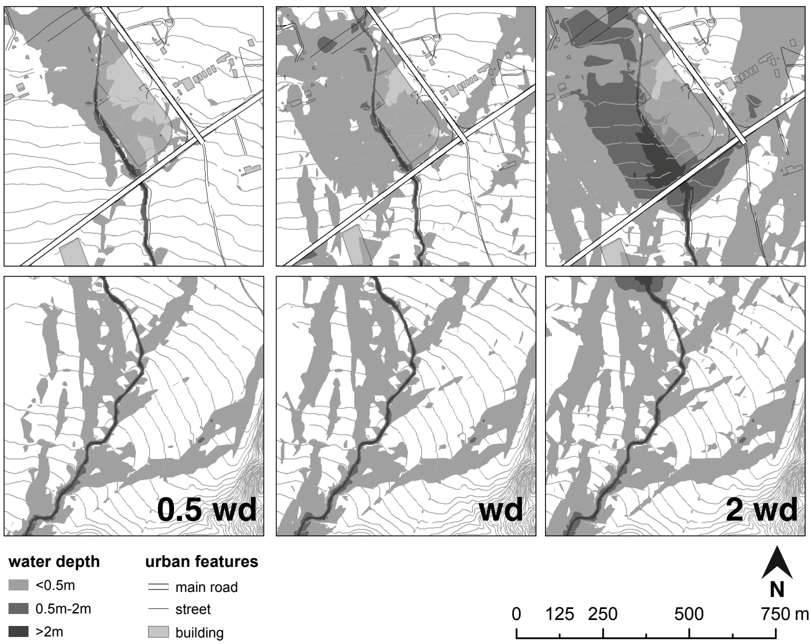


Figure 6.10. Wetting / drying and flood processes representation. KIK project

On a whole, the chosen parameters seem to perform well. We notice, especially at the Marrakech road crossing point in the KIK simulation, that the model systematically fails to depict the obstruction role of this road together with the undersized culvert equipment in place. We suggest that the topographic base (DTM) may not be sufficiently accurate to represent such structures, impeding therefore good process representation. We remark that the analysis results are dependent of the chosen range of values for each parameter, as we performed simulations with the half and the double of the initial parameter values. Therefore, not exploring larger parameter ranges might have an effect on the model performance. Nevertheless, the initial parameter choice was justified by the need to achieve the necessary model precision with reasonable computation costs.

Parameter	Variation	K	K_1	F	O
Resolution	3m	32.45	30.51	46.22	66.45
	6m	30.62	28.81	45.18	65.54
Roughness	*n*/2[4]	21.87	19.58	39.2	61.31
	*n**2	31.42	30.91	46.51	65.85
Eddy viscosity	0.4	32.45	30.51	46.22	66.45
	0.8	31.76	29.51	45.57	66.13

Table 6.12. Accuracy estimates for TUFLOW parameter variation (BM).

Parameter	Variation	Kappa	Kappa_wet	F	Overall
Resolution	2m	25.25	26.16	35.98	65.12
	3m	22.9	38.98	40.11	59.8
	6m	30.34	29.79	38.76	67.65
Roughness	*n*/2	15.41	22.37	34.70	57.24
	*n**2	25.17	35.02	39.56	62.52
Eddy viscosity	0.2	22.9	38.98	40.11	59.8
	0.4	28.72	30.19	38.25	66.62
Wetting/Drying (depth, cell side)	0.0125, 0.025	30.04	31.22	38.88	67.34
	0.05, 0.1	25.17	35.02	39.56	62.52

Table 6.13. Accuracy estimates for TUFLOW parameter variation (KIK).

Indeed, the initial 3m-grid is fairly precise, and satisfactory for flood process representation in urban areas (Hunter et al. 2008) and hazard mapping purposes. The roughness parameter choice is based on land use classes in order to depict the variation in surface friction. It is discussed in literature (Lane 2005, Yu & Lane 2006) that the roughness coefficient can be used as an effective parameter for model calibration as its effective relationship to real surfaces is difficult to assess. Indeed, this empirical parameter stems from steady flow assumptions applied to unsteady flows (French 1985). The relative sensitivity of this parameter, emphasized in Figure 6.5 and Figure

[4] n varies according to land use classes (see table 6.5).

6.6, suggests that exploring a larger value range could enhance the calibration results, as it was proved for example by Yu & Lane (2006).

6.4. Model extrapolation for flood hazard assessment

Flood simulations were performed, on the basis of the described model, for rainfall events corresponding to the 20, 50, and 100-year return period. As described in Chapter 6, there is no possibility to assess flood frequency on a statistical basis for the catchments draining Beni Mellal as no hydrometric data is available.

Flood extent, water depth and velocity maps were produced for further use within the flood hazard assessment procedure according to the Swiss guidelines. For the Handak stream, a supplementary flood simulation was performed using the modelled hydrograph upstream of the flood-reducing dam for the 100-year event in order to assess possible residual risks related to this hydraulic structure. The results are presented in Appendices 6-12.

Maximum flood extent does not change significantly between flood scenarios for the BM project, but flood intensity does: water velocity becomes one hazardous element for higher magnitude floods (Appendices 9-11). We equally addressed residual flood hazard related to the existing Handak flood-reduction dam by simulating the highest magnitude event in absence of this structure, i.e. by using the flood hydrograph as modelled upstream of the dam. No extent changes could be detected. However, higher intensity levels are expected to occur especially where urban structures play a flood-obstruction role (Appendix 12). For the KIK model, flood extent changes between flood scenarios as flood branches tend to join in larger inundation areas with higher magnitude floods (Appendices 6-8). Nevertheless, given flow path uncertainty related to the complex alluvial fan morphology, hazard should be addressed on the whole flood-prone area as delineated by the flood external boundaries.

6.5. Discussion

The objective of this chapter was to obtain, via hydraulic modelling, flood extent and intensity maps for the 20, 50 and 100-year recurrence time events. Method choice and input parameters resulted of a compromise between computational needs, accuracy needs and cost-effectiveness. We further discuss the contributions and shortcomings of the approach described in this chapter.

6.5.1. Method contributions and shortcomings

We addressed flood modelling in a two-step manner by testing two different models. This approach allowed us to:

- Find the most appropriate model for the given environment (specific topography problems, flood type)
- Integrate the findings of the 1D model to the 2D one (channel geometry as created in HEC-RAS was integrated to the existing DTM of the Beni Mellal urban plan allowing for better channel representation within the 2D domain).

On the other hand, this approach has certain shortcomings:

- Specifying channel geometry in the 1D approach was time consuming and the results second-rate;
- The final model requires commercial licensing, which means the cost-effectiveness objective could not be attained.

Hydraulic modelling proved to be essential to flood hazard assessment as it provided measurable data to characterize known events as well as high magnitude - low frequency flood scenarios:

- Flood intensity could be assessed via maximum water depth and velocity maps; flood frequency is characterized at the map level via flood maximum extents for given return period flood events;
- This contribution is necessary to hazard assessment and could not be attained using solely geomorphic or descriptive methods;
- However, field collected data (flood extent, active hydro-geomorphic zones) proved useful for model findings verification and allowed us to better understand the uncertainty related to the model.

The 2-dimensional hydrodynamic model TUFLOW modelled flood processes realistically on our study site, especially given topographic data uncertainties.

- Indeed, flooding on complex alluvial fan topography specific to the studied area as well as flooding of the complex Day junction point, where floodwaters from three streams mix, were best described by this model. Even though TUFLOW was not designed especially for alluvial fan flood modelling, it proved to be very suited for this specific environment.
- The use of relatively high grid resolutions allowed reasonable depiction of channel flow processes within the 2D domain.
- Even though hazard map design does not necessarily require specifying flood propagation in time, unsteady flow models like TUFLOW are better suited for describing flash-flood events specific of the studied area.

Use of the 2D model revealed relative difficulties.

- Flood processes were unequally represented in the two areas codenamed KIK and BM: better accuracy and process representation of flooding were achieved on the BM area concerning the streams Aïn el Ghazi, Sabek and Handak. As parameter-tuning did not provide significantly better results for flood related to the Kikou stream, we suggest that the elevation data could not capture the obstruction effect of the Marrakech route, failing therefore to represent more accurately flood extents. On the other hand, we may suggest that field monitoring of flood extent may have been incomplete on the fan surface upstream of the Marrakech road.
- An important issue of the 2D model was related to the computational effort required for simulations and model calibration. Indeed, using relatively high spatial resolutions requires setting very small time-steps (for 3 m resolution

time-step is 1.5 seconds or less for better stability) thereby increasing computational time and required memory. Calibrating the model to lower resolutions has proven to be unrealistic (Hardy et al. 1999).

Sensitivity analysis of the model's parameters provided us good insights on model behaviour.

- On one hand, it allowed drawing conclusions about uncertainty sources related to the model parameters but also to other input data, especially the elevation model. This analysis also helped questioning the verification method used (i.e. field monitoring of maximum flood extents) and its ability to accurately represent field reality.
- On the other hand, sensitivity analysis performed in the limited range of values of a parameter multiplied by of 0.5 to 2 had little effects on accuracy gain for this particular study case.

6.5.2. Method applicability to similar studies

Hydraulic modelling is essential for hazard assessment and mapping according to the Swiss methodology (ARE, OFEG, OFEFP 2005). This study suggests that the model choice should be oriented according to the considered environment: 2D hydraulic models are necessary for obtaining realistic results in piedmont regions with alluvial fan morphologies and complex river junctions comparable to this study. Moreover, when dealing with fast-propagating flash floods, unsteady flow modelling should be undertaken in order to correctly assess flood intensity.

In this approach, several methods were integrated: hydrologic modelling provided discharge inputs to the model while flood extent mapping via high water marks proved useful to process understanding and model verification. We suggest that hydraulic flood models should be integrated to this type of holistic approach even though they provide alone enough elements for flood hazard assessment in terms of extent and intensity. We consider that hazard assessment requires multidisciplinary skills (geomorphic, hydrologic, hydraulic) so that final results account for the natural and human environment's complexity.

This study showed that field-mapped flood extents might present certain limitations as model verification means. That is, in complex topographic conditions, mapping the flood external boundaries may be insufficient if certain areas inside these boundaries remain dry. When possible, field monitoring should be supported by flood extent mapping procedures that use airborne data (satellite or aerial imagery). However, field mapping remains necessary in the absence of remotely sensed data and may be necessary for reality proofing of airborne data cartography of flood extents or water depths.

The applicability of this method meets the challenge of the multidisciplinary character of flood studies. As proper modelling requires relatively specialized engineering skills, we suggest that modelling should be undertaken by hydraulicians in collaboration with people who have the geomorphic or hydrologic skills necessary to this type of holistic approach.

Another challenge, extensively encountered in developing countries, is related to data availability that can be absolute when no data exists or relative when the data exists but cannot be accessed. In this specific case, the local authorities gracefully provided topographic data. However elevation data resolution was lower than model grid resolution as the DTM was based upon contour line interpolation and channel geometry had to be reconstructed manually to achieve enough topographic accuracy.

Finally, method applicability may be constrained by financial costs related to software licensing and required computational power. As stated earlier in this chapter, the cost-effectiveness objective of this study could not be attained as the 2D hydraulic model we used was not available in open-source.

6.6. Conclusion

Flood hydraulic modelling represents an essential step in flood hazard assessment and mapping as this method provides the numerical estimates of inundation intensity and spatial extent necessary for quantitative hazard description in the studied territory. The objective of this chapter consisted of providing these estimates as a map for three magnitude-frequency event scenarios: the 20, 50 and 100-year return period floods. Flood depth, velocity and extent maps were produced using a 2-dimensional hydrodynamic model, best-suited for flood modelling in complex topography such as the studied area alluvial fan environment. Flood inundation modelling of a known and field-monitored event was performed in order to attain model validity necessary for its extrapolation to the given recurrence time scenarios that form the base for flood hazard mapping.

The obtained flood intensity maps for the three given frequencies represent the necessary inputs for the next step consisting of indicative flood hazard map design for the urban area of Beni Mellal. They represent also the integrated result of a multidisciplinary approach that addressed flood hazard in a holistic manner that accounted for the studied area's hydro-geomorphic individuality, the catchments' hydro-climatic potential and the urban setting features.

In the next chapter we address indicative hazard map design for the city of Beni Mellal and the applicability of the Swiss method adaptation in similar contexts.

7. Beni Mellal indicative danger map

In the previous chapters we have presented the necessary steps for obtaining the required data inputs for flood hazard maps design according to the Swiss hazard mapping guidelines. Indeed, hazard identification in the field as well as hazard assessment in terms of frequency and intensity were necessary for the hazard mapping purposes. This chapter deals with hazard mapping according to the Swiss guidelines and the necessary adaptations we undertook in the Moroccan context. The final output of this project, i.e. the indicative flood danger map of Beni Mellal in Morocco, is presented along with the possible consequences this document may have on planning.

7.1. Hazard map design: Swiss guidelines and adaptations

Two types of hazard maps are produced in Switzerland: the hazard indication maps assess hazardous phenomena at a regional scale, mostly in terms of spatial extent of their respective consequences, while danger maps address these phenomena at finer, local scales, giving a detailed hazard magnitude description along with planning indications (ARE, OFEG, OFEFP 2005, see Chapter 2). Hazard magnitude is calculated using the Swiss hazard matrix.

7.1.1. The Swiss hazard matrix

Unlike other European procedures that assess risks related to natural phenomena like floods, the Swiss methodology aims to assess and map hazard to further assign spatial danger specifications and protection objectives for the hazard-exposed objects. The Swiss hazard matrix embeds these two characteristics: on one hand it assesses hazard-related threat in terms of phenomenon intensity and frequency; on the other hand its colour code is related to planning approaches for the designed areas (Figure 7.1).

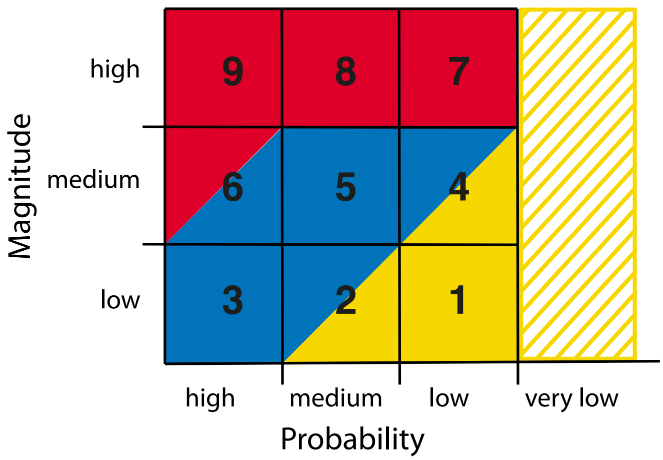


Figure 7.1. The Swiss hazard matrix. Red = high threat, blue = medium threat, yellow = low threat, and white-yellow = residual hazard zone.

Frequency / intensity thresholds for hazard estimation

The Swiss hazard matrix expresses hazard intensity and probability as qualitative degrees (very low, low, medium, high). Nevertheless, these specifications are based on quantitative measures of the concerned criteria. Flood intensity for example is expressed in terms of flood characteristics that have direct, threatening consequences at the human scale, such as the inundation depth or the flow velocity. These characteristics are envisioned in terms of actual danger for human lives, animals and buildings (Loat & Petrascheck 1997): water depth higher than 2 m is considered to be threatening for people's lives; the product of water velocity and depth yielding more than $2 m^2/s$ represents a comparable threat for fast-propagating flash floods for humans as well as for buildings that are expected to suddenly collapse. In this logic, flood intensity thresholds were assigned according to their consequences on exposed people and assets (Table 7.1).

Intensity measure criterion	Low	Medium	High
Static flood: water depth	$\boldsymbol{H < 0.5\ \mathrm{m}}$	$\boldsymbol{0.5\ \mathrm{m} < H < 2\ \mathrm{m}}$	$\boldsymbol{H > 2\ \mathrm{m}}$
Dynamic flood: water depth*velocity	$\boldsymbol{Hv < 0.5\ m^2/s}$	$\boldsymbol{0.5\ m^2/s < Hv < 2\ m^2/s}$	$\boldsymbol{Hv > 2\ m^2/s}$

Table 7.1. Quantitative thresholds for low, medium and high flood intensity in static and dynamic flooding events.

Flood frequency or more precisely the probability of occurrence of a given event represents the other variable of the hazard matrix. Flood frequency influences hazard in time and in space. From a temporal point of view, frequent flood events must be addressed by priority measures of hazard mitigation as they threaten exposed people and assets on a regular basis. Nevertheless, frequent floods show lower intensities than rare or extreme events, which can trigger natural disasters if not addressed properly. Low frequency – high magnitude floods arise the problem of actually assessing their probability of occurrence for planning purposes on the short or medium term. The relationship between recurrence period and recurrence probability can be expressed for a given period of time (Loat & Petrascheck 1997):

$$p = 1 - \left(1 - {}^{1}/_{T}\right)^{n} \tag{7.1}$$

where p = event's probability of occurrence for the given period n and T = the event's return period.

Flood event recurrence probability	Low	Medium	High
Recurrence period	300-year	100-year	30-year
Probability of occurrence (20 years)	6%	18%	49%
Probability of occurrence (50 years)	15%	40%	82%

Table 7.2. Thresholds for low, medium, and high flood event recurrence probability and the significance of flood recurrence periods for the short and medium term.

One can notice that for the medium term, rare events yield relatively high probabilities of occurrence (see Table 7.2).

In most cases, low frequency – high magnitude flood events expose larger areas to damage. For example, in alluvial plains, the river floodplain may be inundated only during this type of event. The spatial imprint of given recurrence events is used in hazard mapping as a frequency criterion. Thresholds are assigned to classify events as high, medium and low frequency (Table 7.2). The 30 and 300-year thresholds originate in the avalanche hazard mapping methodology that was the first hazard to be addressed from the planning point of view in Switzerland (OFF 1984, Loat & Petrascheck 1997). The 100-year threshold is related to more specific flood hazard applications. For example the French-developed *Méthode hydrogéomorphologique* (Ballais et al. 2011) suggests that the outer limits of the alluvial floodplain equally marks the spatial extent of the 100-year flood; moreover, the 100-year flood represents the main criterion for flood hazard assessment in the United States (FEMA, BESR, NRC 2009).

Moreover, low frequency - high magnitude flood events arise the problematic of risk or hazard memory i.e. hazard or risk acknowledgment turns out to be difficult if these low-frequency events were not witnessed by the exposed communities. In the context of emergent urbanization in hazard-exposed areas like the specific study case of Beni Mellal, community awareness to hazard represents an integrative part of the hazard management approach. Likewise, areas protected by active mitigation measures (dikes, dams, etc.) behold a residual risk or hazard, since no protection structure is fail-safe. Yet, protection structures may induce a false sense of security to the exposed communities requiring therefore hazard awareness measures as well as the implementation of emergency procedures of alert and evacuation (Loat & Petrascheck 1997).

Colour code and its significance for planning

The Swiss hazard matrix depicts hazard-related threat as a three-degree variable, represented by the colours red, blue, and yellow. White-yellow strips are used to depict residual threat. On one hand, the three colours represent the degree of hazard threatening humans, animals and high-value assets inside and outside buildings (Loat & Petrascheck 1997). On the other hand, each colour is bound by a series of instructions relative to planning: the zones delineated on danger maps are to be integrated to the local planning documents and intervene in building policies (Table 7.3).

Hazard graduation and its consequences on humans, animals and high-value assets as well as the prescriptions related to planning are summarized in Table 7.3. The red zone, concerned by prohibition measures, corresponds to all areas of high flooding probability and those areas expected to witness high intensities during rare events. The blue zone, corresponding to medium frequency and magnitude events, is a regulation one, where constructions for housing and economic activities are possible, provided specific protection measures. The yellow zone is an awareness-making zone, where inhabitants must acknowledge flood hazard in order to "live" with it. The inhabitants' responsibility is strongly engaged in this zone. The residual danger zone, marked by white-yellow strips is also an awareness-making zone. It has been created to account for hazards related to very rare events as well as for those areas protected by active measures (dams, dikes).

Hazard matrix colour	Danger significance	Zone type	Planning prescriptions
Red	- People and animals in danger inside and outside buildings - Buildings sudden collapse danger - High frequency-low intensity events: people in danger outside buildings	Interdiction	- Interdiction of housing projects - Decommission of unused construction zones - Damaged houses: interdiction to rebuild - Existing housing zones: active measures of protection
Blue	- People in danger outside buildings - Damage to buildings	Regulation	- Constructions authorized provided conditions
Yellow	- Little danger to people - Important damage inside buildings (caves)	Awareness	- Protection for sensitive assets - Awareness-making procedures
White-Yellow	- Possible high impacts on people and buildings	Awareness	- Emergency plans - Protection for sensitive assets

Table 7.3. Hazard matrix colour code signification

Swiss hazard matrix and hazard perception

Floods, as any natural hazards are part of the everyday reality for many hazard-exposed communities. In order to "live with" hazard, these communities dispose of several coping strategies. Burton et al. (1978) showed that at the community level and depending on the hazard gravity, three hazard-related attitudes could be defined. First, when the biologic and individual adaptation strategies become inefficient, the hazard awareness occurs, as the community is brought to bear the costs of hazard-induced damages. Further on, communities are brought to deal with hazard actively by changing the event itself or by preventing its effects: the action threshold is attained. Finally, when hazard cannot be modified or be tolerated, the ultimate coping strategy consists of changing hazard-exposed areas' utility or simply leaving those areas. Schoeneich & Busset-Henchoz (1998) explained the perception thresholds as a function of cognitive dissonance-reduction strategies.

The Swiss hazard matrix colour code corresponds to the three perception thresholds described above. Indeed, the red zone delineates those areas where the intolerance threshold was exceeded; the blue zone corresponds to the action threshold while the yellow one delineates those areas where hazard awareness occurs and where individual and community responsibility is involved (Schoeneich et al. 1997, Schoeneich & Busset-Henchoz 1998).

Public perception of mapped danger zones as well as map acceptability is highly dependent of the colour choice. We suggest the Swiss hazard matrix achieves a good compromise between marking gradual hazard magnitude and the planning significance of danger zones. Indeed, the red colour clearly marks high hazard as well as the strict prohibitive sense of the delimited zones. The blue colour could be differently interpreted given the type of hazard addressed (Schoeneich et al. 1997) but still achieves depicting the sense of this regulation zone, where development is allowed provided specific protection measures. The yellow zone marks well lower danger but reminds inhabitants that hazard exposition is still a reality in the concerned area.

The colour code of the Swiss hazard matrix not only depicts hazard in a gradual manner, but it also contains specific planning prescriptions for the concerned areas. Thus, this approach represents a comprehensive tool for assessing and mitigating flood hazard. The Swiss hazard matrix also responds in a comprehensive way to the risk or hazard perception problematic that implies on one hand hazard coping approaches and on the other hand the hazard map’s acceptability for the public.

7.1.2. Practical issues and limitations of the Swiss hazard matrix

The Swiss methodology proposes a unified mapping system for the whole territory, according to uniform assessment criteria. In practice, though, the application of the Swiss system and especially the Swiss hazard matrix revealed certain limitations. As no literature is yet available on this issue, the conclusions drawn below result of a series of interviews with practitioners.

First, there is a lack of consensus among practitioners regarding the matrix colour choice. Indeed, if the meaning of the red colour is clear for end-users, the other two colours are less easily accepted. On one hand, the blue colour is often thought to represent water-related hazards, as the adaptation of the Swiss system abroad has revealed (Zimmermann et al. 2005, MZ 2013); on the other hand, for some users, the yellow colour represents intuitively a more severe hazard than the blue one (RG 2013). Proposed alternatives to the present colour code would be the traffic light system (red-yellow-green) or a gradient of red-orange-yellow. One could note that the traffic light code may also be confusing, as the green colour can intuitively be related to the concept of no hazard.

Moreover, there is an important issue regarding the way danger zones are assigned within the matrix. On one hand, the existence of “half-cases” (cases 2, 4, and 6 of the matrix) may be confusing and result in slightly different assessments; thus, unitary guidelines at the cantonal level for instance should guarantee mapping equity throughout the concerned territory. Moreover, the convolution of hazard magnitude and probability can result in danger assignment, which is difficult to transpose in planning (MZ 2013, RG 2013). For example, the red zone is assigned for high magnitude events with a return period of 30 to 300 years, while these probabilities have different relevance for planning. Thus, there is a risk to impede development on surfaces that may rarely be affected by a flood. In this case, practitioners propose a gradient of red zones with specific planning constraints for each probability of recurrence (MZ 2013, EB 2013). On the other hand, areas that may witness water depths up to 2 meters during very rare events can, according to the matrix, be assigned to the low danger zone (case 4 of the matrix, Figure 7.1). Or, in the yellow zone, no planning constrains are effective. Thus, case-by-case approach to the matrix seems to be more desirable in practice for planning purposes, and more detail is needed when addressing specific magnitude-frequency cases.

One respondent raised the problem of matrix legibility, as the probability axis is read from right to left (lower probability is read first, followed by higher probability of recurrence). In this respondent's opinion, the matrix is difficult to use and to communicate: as such, the canton of Lucerne uses a matrix where the probability axis is read from left to right (RG 2013).

Finally, there is a lack of consensus between the matrix prescriptions and the mitigation practice in that the selected medium and low frequency thresholds (100 and 300-year) are not consistent with the mitigation policy in use in Switzerland (MZ 2013, RG 2013). Indeed, structural measures are usually planned for maximum 50-year or 100-year return period events, depending on financial resources (EB 2013, MZ 2013, RG 2013). As such, areas protected with structural measures may still contain large danger zones where planning activities are constrained by the existence of a danger map.

7.1.3. This study's approach to danger map design

The aim of this project is to design an indicative flood danger map for the city of Beni Mellal by adapting the Swiss hazard mapping method to the studied areas' environment. A joint study underwent the same approach for the specific site of the city of Fez (Lasri 2013). Moreover, the adapted approach could be implemented in similar locations and socio-economic contexts.

The indicative danger map we designed represents a **hybrid document** between the Swiss regional, hazard indication maps, and the more detailed, municipal danger maps. Indeed, the map we designed is an "indicative" document in that the chosen design scale is relatively coarse (1:15'000 for the Beni Mellal map, 1:20'000 for the Fez map). Secondly, the relative scarcity of available input data for hazard assessment (hydro-meteorological, land use and soils, elevation data) may restrain the precision and quality of the assessment. Finally, Swiss danger maps are integrated to municipal planning documents and building regulations; therefore, the cadastral scale binds their precision. This type of precision as well as the planning consequences of the danger map could not be attained in the study case. In conclusion, the aim of this map is to assess hazard at a reasonable scale and provide planners the necessary tools for decision-making in the context of urban areas exposed to flood hazard.

On the other hand, the map designed in this study contains the danger assessment characteristics of the Swiss hazard matrix, where floods are assessed according to their intensity and occurrence probability delineating zones of interdiction (red), regulation (blue) and awareness-making (yellow). In this particular case, the Swiss hazard matrix colour code represents a series of recommendations for planners according to hazard assessment, as no legal base is yet available in Morocco for integrating danger maps to urban planning. Again, the indicative hazard map as designed by this project consists of a decision-making tool for further passive flood hazard mitigation measures.

An important adaptation in hazard assessment was undertaken for the definition of

recurrence probability thresholds. The selected hazard class limits are presented in Table 7.4. These thresholds are typically used in Morocco for classifying floods probability. The significance of the 100-year flood for hazard assessment practice was emphasized earlier in this chapter (Section 7.1.1) while the use of the other two limits is justified by the practice in similar studies in Morocco (ADI 2004; ADI, ABHOER 2006). The planning-oriented character of this hazard assessment justifies setting the high recurrence event as the 20-year return period. Thus, planning in the short-to-medium term (availability period of one or two subsequent master plans) is addressed within the indicative danger map. We expect the change in medium and low probability thresholds to influence the final flood hazard assessment by overestimation of the low-frequency events. Nonetheless, using probability thresholds that are related to the local practice (calibration of protection objects) can improve the credibility of the danger map. In this line, the Swiss methodology is not adapted to the field reality in Switzerland, where protection objects are calibrated to maximum 100-year events (oral information, MZ 2013, RG 2013).

Flood event recurrence probability	Low	Medium	High
Recurrence period (this study)	100-year	50-year	20-year
Recurrence period (Swiss method)	300-year	100-year	30-year

Table 7.4. Selected thresholds for low, medium, and high flood event recurrence probability in the Moroccan case and the Swiss method.

For practical reasons, the indicative danger map presents the flood hazard situation in **July 2010**. Indeed, this study could not account for the on-going mitigation measures undertaken at the urban level during the study's monitoring phase and further. We accounted therefore for the completed mitigation structures on the Handak stream: flood-reduction dam, longitudinal protection walls, Day junction transformation. Nevertheless, the projected and on-going deviation works of the Sabek and Aïn el Ghazi streams as well as the protection structures and enlargement of the Kikou stream were not accounted for. Therefore, flood hazard as depicted by this map corresponds to the natural flooding behaviour of the concerned streams and would ultimately represent the residual hazard related to the undertaken mitigation measures.

Spatially, even though this study focuses on the urban area of Beni Mellal, the depicted flood-related danger zones overstep the actual urban boundaries for several reasons. First, we wished to depict the natural behaviour of the studied streams. Then, since Beni Mellal is a fast-developing city affected by intensive urban sprawl, we wished to depict hazard for eventual further modifications of the urban perimeter. Moreover, some sensitive assets like the city's industrial area or the weekly market place are situated at the urban limit. Finally, very sensitive illegal housing developed at the urban boundaries (e.g. Nkhila settlement on Day stream, Oulad Attou settlement situated in the hazardous location where the Kikou stream crosses a major irrigation channel. Thus we judged necessary to assess hazard at these locations.

7.1.4. Hazard map design workflow

The main inputs for the danger map design are the quantitative flood intensity and probability estimates obtained via hydraulic modelling of flood inundation within the urban area of the city of Beni Mellal.

Intensity maps represent essential documents for flood hazard assessment. They provide the necessary information for local active measures of protection as well as for designing alert and evacuation plans (ARE, OFEG, OFEFP 2005). We used two intensity measures, according to the Swiss hazard map guidelines: water depth H and the product of water depth and velocity H*v (Figure 7.2) in order to account for the specific flooding characteristics in Beni Mellal. Flood depth is necessarily assessed for hazard mapping; moreover, the role of flow velocity becomes important for hazard assessment due to the fast-propagating aspect of floods occurring in the studied area.

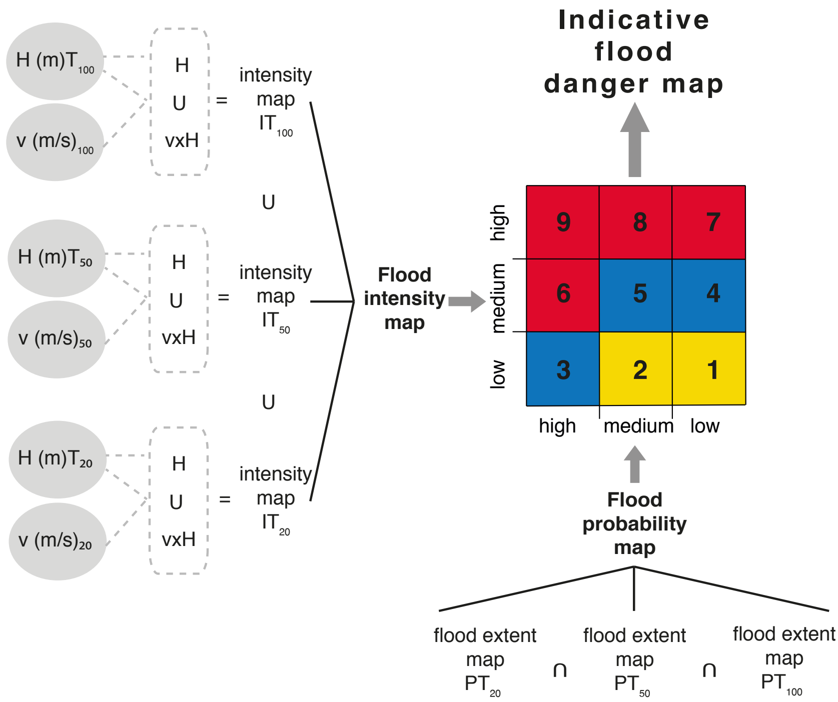


Figure 7.2. Indicative danger map design. H (m) = water depth; v (m/s) = water velocity; T_{100}, T_{50}, T_{20} = Flood event of 100, 50 and 20-year return period; IT_{100}, IT_{50}, IT_{20} = Intensity maps for given return period events; PT_{100}, PT_{50}, PT_{20} = Probability maps for given return period events.

The quantitative water depth and depth-velocity data was first classified into low, medium and high intensity categories according to the Swiss hazard matrix thresholds (Table 7.1). We produced intensity maps for the considered return period of 20, 50 and 100-year events, by merging the individual water depth and depth-velocity estimates. The 100-year event is expected to produce the higher magnitude and maximum inundation extent; therefore, it represents the reference event of the indicative danger map.

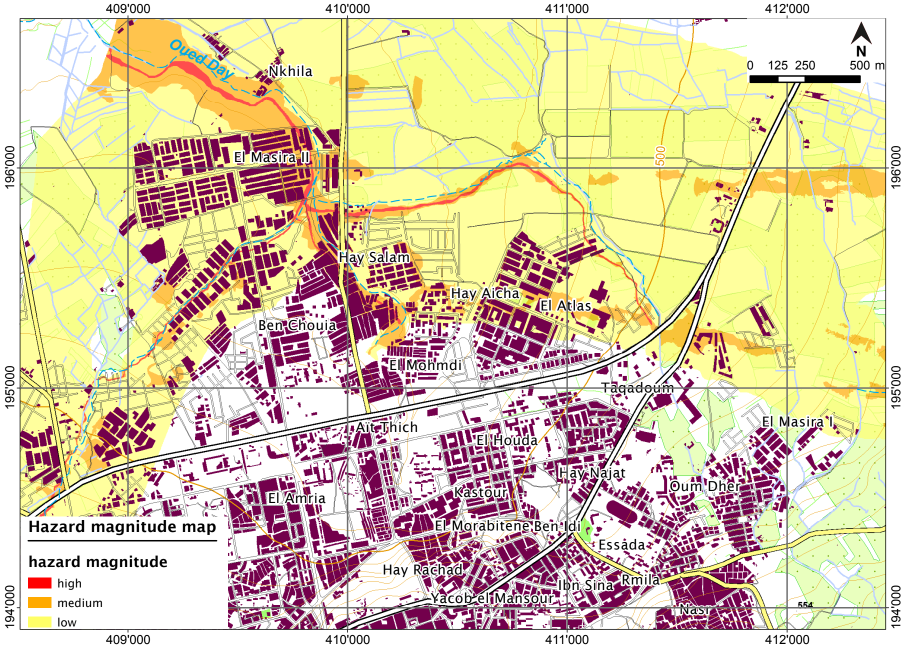


Figure 7.3. Flood intensity (magnitude) map. Zoom on the Day junction point

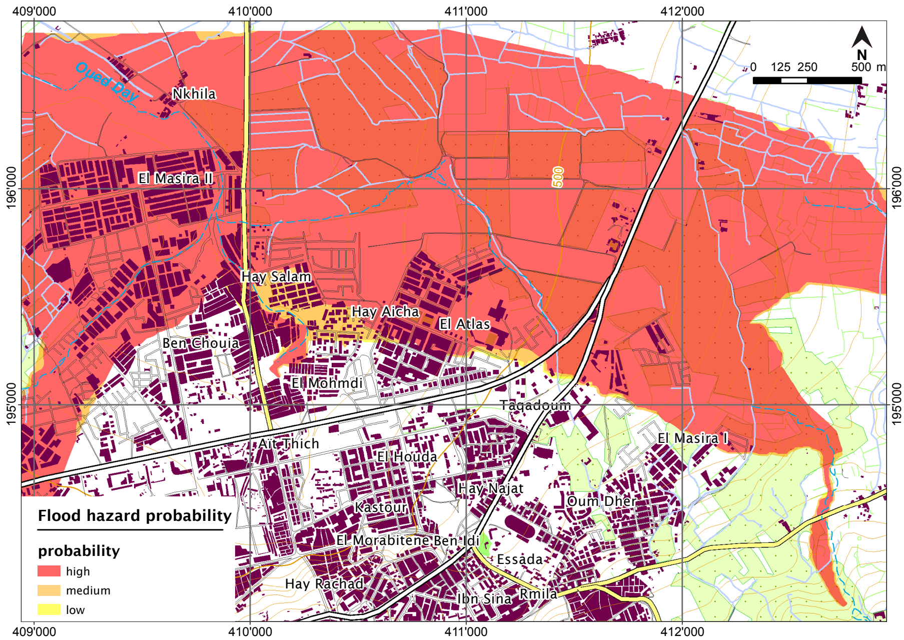


Figure 7.4. Flood probability map. Zoom on the Day junction point.

In order to account for eventual high intensities specific to the lower magnitude events of 50 and 20-year return period, the three intensity maps IT_{100}, IT_{50}, IT_{20} (Figure 7.2) were merged in order to produce the flood intensity maps (Figure 7.3, Figure 7.5). The higher intensity class resulting of maps intersection was systematically assigned to the final intensity map.

The probability term of the Swiss hazard matrix consists in the maximum flood extent maps as obtained via hydraulic modelling of flood inundation in Beni Mellal for the given events of 100, 50 and 20-year return period (see maps PT_{100}, PT_{50}, PT_{20} in Figure 7.2). By their intersection, we obtained the final flood probability map consisting of the low, medium, respectively high probability classes (Figure 7.4, Figure 7.6).

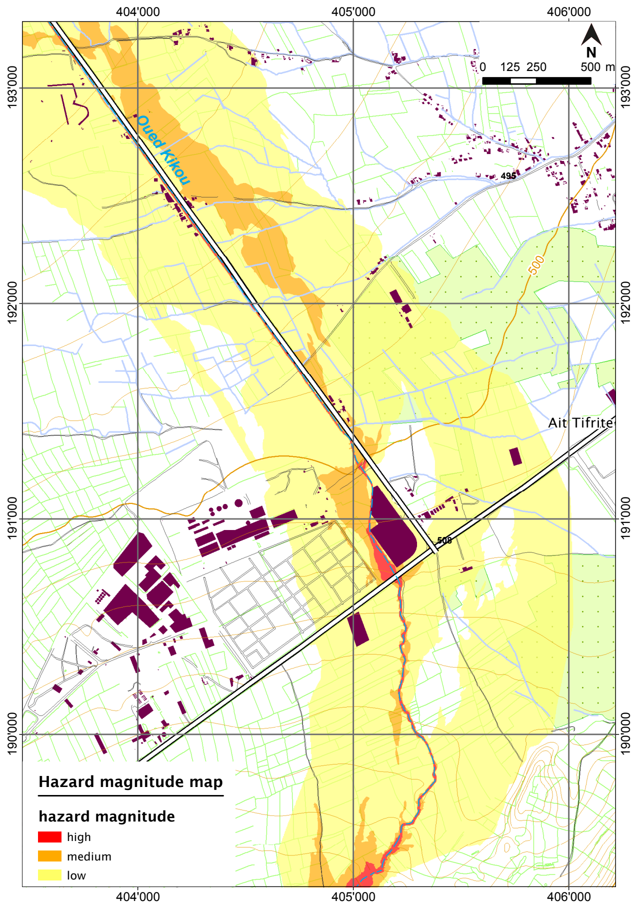


Figure 7.5. Flood intensity (magnitude) map. Zoom on the Kikou stream.

Subsequently, the intensity and probability maps were intersected. In order to obtain the indicative flood danger map for the city of Beni Mellal; the map resulting from this intersection was classified according to the Swiss hazard matrix. Degrees of low (yellow), medium (blue) and high (red) danger were assigned Figure 7.2).

The colour choice and its related significance represent an adaptation of the Swiss hazard matrix. We chose to assign low danger values (yellow) to those areas situated in low and medium frequency and low magnitude areas (cases 1 and 2 of the hazard matrix, Figure 7.2). By choosing the case 2 as low danger zone, we avoid bias related to the change of the initial probability thresholds for low intensity flood situations (see Section 7.1.3 related to the probability threshold choice). High frequency – low intensity areas (case 3) as well as areas concerned with medium intensity floods of moderate frequency (cases 5, 4) were assigned the medium danger value (blue). All high intensity areas (cases 7, 8, 9 as well as the medium intensity-high frequency case (6) were assigned the high danger value (red).

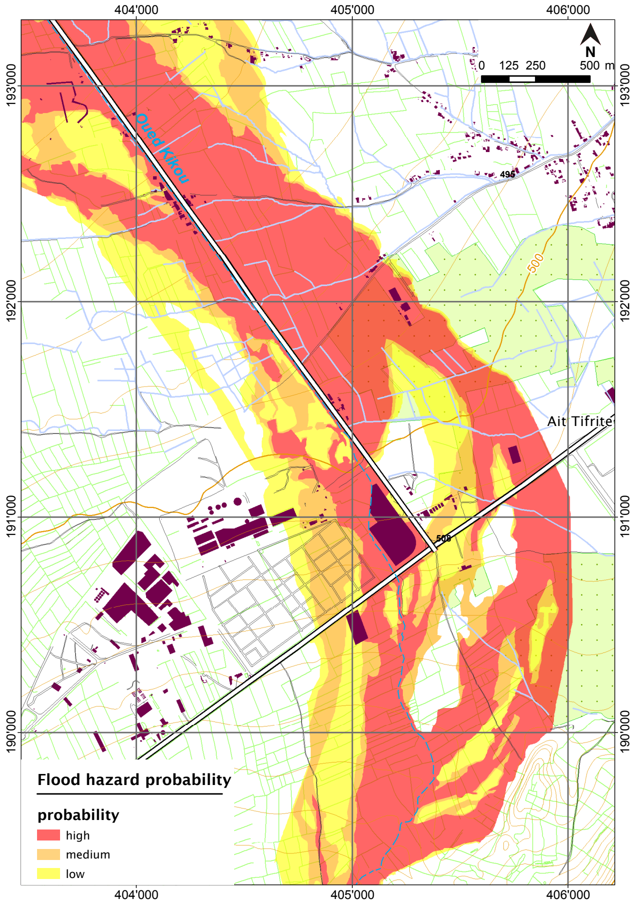


Figure 7.6. Flood probability map. Zoom on the Kikou stream.

7.2. Indicative flood danger map of Beni Mellal

The indicative flood danger map of Beni Mellal represents the final "product" of this project, according to the SDC assignment (see the attached Beni Mellal indicative danger map). A similar map was produced by the joint project for Fez (Lasri 2013). This map was designed as a decision-making tool the local authorities and planners could use to orient future urban development by using passive flood hazard mitigation measures. The map is also an adaptation of the Swiss hazard mapping procedure to this study's area of focus. In this section we present the findings related to the flood hazard assessment as well as the map's consequences for subsequent planning developments. The results of hazard assessment as reflected by the indicative danger map are presented for two specific cases: on one hand, the streams that drain the city centre of Beni Mellal (Handak, Sabek and Aïn el Ghazi (Figure 7.7) and on the other hand, the Kikou stream that drains the western end of the urban perimeter, threatening mainly the city's industrial district (Figure 7.9).

7.2.1. Handak, Sabek, and Aïn el Ghazi streams

Indicative danger map findings

These streams naturally flood the gently sloping surfaces of ancient alluvial fans. Handak crosses for a few kilometres a densely urbanized sector of the city: thus, hazard mitigation structures were first built along this stream. Their role in flood development was taken into account. Sabek and Aïn el Ghazi maintained a quasi-natural functioning pattern at the reference moment of this map (July 2010). Indeed, local streambed enlargement or deepening was undertaken at specific points on the upstream reaches of these streams in order to avoid the consequences of flooding by overspill (field observations).

High danger zones (red) are mainly located in streambeds and their close vicinity, at the upstream reaches and close to crossing structures (bridges, culverts) (Figure 7.7). We note here that the active alluvial fan reaches, where sedimentation processes are effective, correspond to the high danger red zone. The lower Day reach, downstream of the junction point behaves as a typical floodplain where high water depth and velocities can be attained as this area drains the entire floodwater volume towards the main collector, Oum-er-Rhbia river situated northern in the Tadla plain.

The medium danger zone (blue) covers almost entirely the flood-prone area drained by the three streams (Figure 7.7). This can be explained by the typical sheet-flooding behaviour of these streams once they reach the gently sloping alluvial fan surfaces. Indeed, unlike riverine floodplains where flood is constrained by the fluvial morphology, on these alluvial fans high and medium frequency floods touch large areas at relative low flood intensities. Thus, maximum flood extents show little modification between the 20, 50 and 100-year events on these gentle slopes; the difference is marked mainly by changes in intensity (water depth and velocity) (Figure 7.4). For instance, larger areas witness high intensities during the 100-year event than during the 20-year event.

Very few areas are situated in the low danger (yellow) zone. This can be explained by the great extension of high frequency-low intensity floods related to the studied steams typical sheet-flood behaviour on the alluvial fan surface.

Indicative danger map significance for planning

The streambed vicinity as well as the crossing structures (bridges, culverts) located in red zone must be protected using active measures especially in the urbanized area along the Handak stream and the Day junction zone (culvert resizing, flow section enlargement).

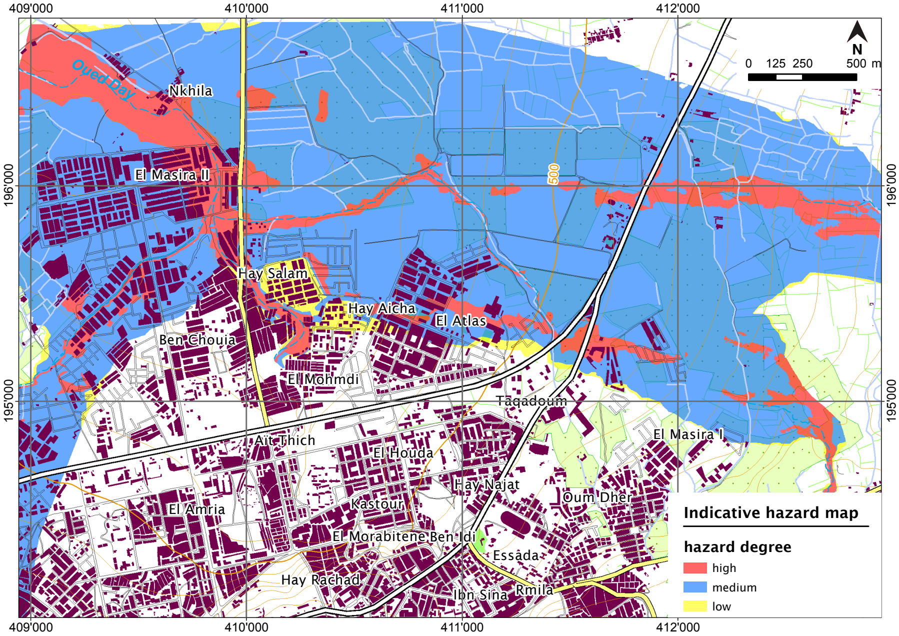


Figure 7.7. Indicative flood danger map. Zoom on the Day junction.

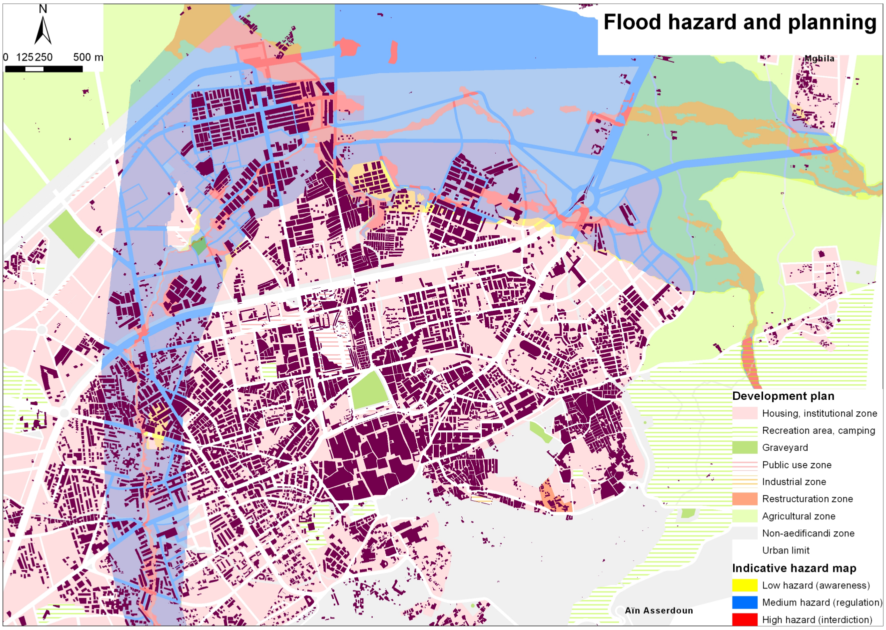


Figure 7.8. The indicative flood danger map versus the present Master plan.

At this point, our suggestion meets the present mitigation strategy adopted by the local authorities, which is based entirely on constructive measures. We note that few planned building zones actually lay in the red zone (Figure 7.8). These zones should change their allotment in order to mitigate flood hazard. Day stream floodplain should be kept building-safe.

The medium danger (blue) zone should be subject to building regulation. The Swiss hazard map methodology states that no new building zones should be defined within the blue zone in forthcoming planning documents (Loat & Petrascheck 1997). Here buildings should fulfil certain security conditions (e.g. higher basements) and inhabitants should be made aware of flood hazard and their responsibilities. Large alluvial fan surfaces are set in the blue zone. Building regulations should account for the typical sheet-flood behaviour of the three streams by allowing water to be channelized and drained downstream.

Actually, the flood mitigation strategy adopted by the local authorities is based on structural modifications of the drainage network using streambed transformations and protection (Handak) and stream deviation (Sabek, Aïn el Ghazi) that are expected to cut the connectivity between the streams and the adjacent fan surface. This strategy is expected to solve the flooding problem related to the typical piedmont morphology consisting of gently sloping alluvial fan surfaces. On the downside, the planned active measures require constant financial involvement for their construction and maintenance. They could equally create a false sense of security that would bring urban surfaces closer to streams and their hazardous floods.

7.2.2. Kikou stream

Indicative danger map findings

Kikou drains a large, little urbanized alluvial fan surface extending from the fan apex northern to the main road Fez – Marrakech; the lower reach downstream of this point is set on the distal fan contact to the Tadla plain. The topographic low corresponding to the stream’s ancient valley bottom was equipped (July 2010) with a highly undersized drainage channel directing floodwaters downstream towards the collector river Oum-er-Rhbia on the Tadla plain. The road and the undersized culvert crossing it represent a highly sensitive point for flood overflow.

Further downstream, floodwaters were channelized along the Beni Mellal - Fkih-ben-Salah regional road according to the topography. The crossing of an important irrigation channel, part of the Tadla plain irrigation system represents another sensitive point where the existing structures were not adapted to the real flow capacity of this stream. Downstream of the Fez – Marrakech main road several industries, the regional weekly market and the several houses along the Fkih-ben-Salah route and the irrigation channel are threatened by this stream’s floods.

The high danger zone (red) is located at the apex, along the river channel and, downstream the Fez – Marrakech route expands along the Fkih-ben-Salah road that follows the topographic low corresponding to this stream’s ancient bed (Figure 7.9).

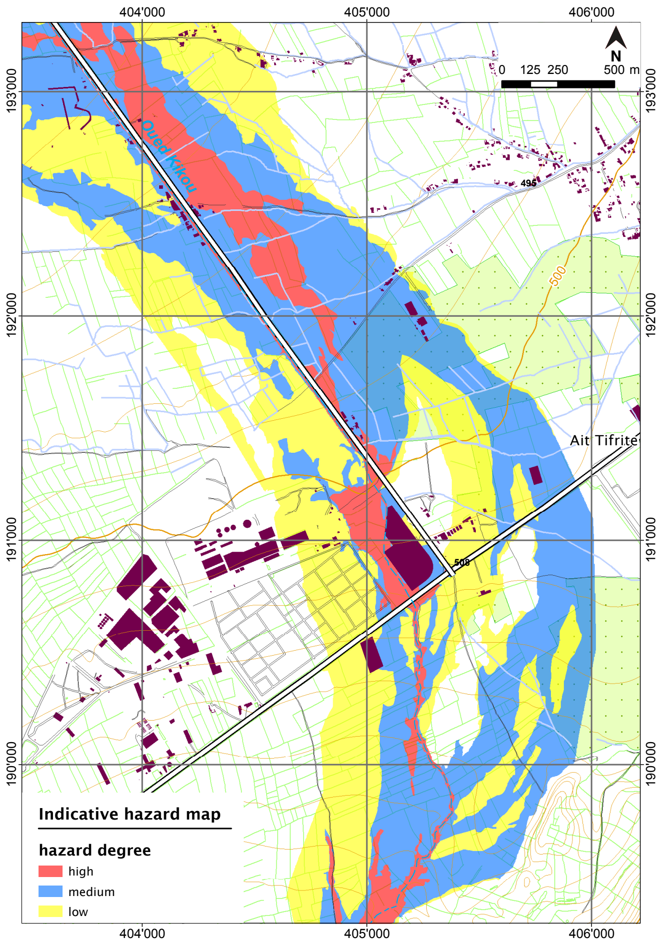


Figure 7.9. Indicative flood hazard map. Zoom on the Kikou stream.

The medium (blue) and low (yellow) hazard zones occupy an important part of the fan surface. This corresponds to a typical alluvial fan flooding pattern characterized by important flow path uncertainty. We suggest that the alluvial fan morphology impacts flooding in a more consistent manner than in the case of the Handak, Sabek and Aïn el Ghazi streams. Maximum flood extents change more steadily according to the given frequency-magnitude event (Figure 7.6). Thus, the probability variable of the hazard matrix impacts more the final hazard assessment than it did in the first presented case.

Downstream of the Fez – Marrakech main road, the blue and yellow zones buffer the topographic low presently occupied by the Fkih-ben-Salah road situated in the red zone. In this area, the hazard zoning corresponds to a transition towards more confined flows, where topography constrains floodwaters along the main flow path (Figure 7.9).

Indicative danger map significance for planning

The main red danger zone situated along the Fkih-ben-Salah road should be subject to active flood mitigation measures that re-create a streambed adapted to the actual flow capacity of Kikou stream. This suggestion is met by the current flood mitigation strategy that consists of streambed enlargement of the whole Kikou reach downstream of the fan apex. In this area structural measures are also necessary as several industries and housing facilities are located here. The blue and yellow danger zones depict the typical alluvial fan characteristic of flow uncertainty that should be accounted for in planning documents. Indeed, even though structural measures might increase streambed capacity, residual hazard related to these structures should be taken into account. In principle, we suggest that no sensitive building should be planned in the affected area and that on-going building should respect certain safety conditions (e.g. higher basements, sufficient sewage system, emergency intervention plans).

Actually, several building projects are in progress along the Fez – Marrakech main road; in our knowledge, flood hazard was not accounted for in their planning.

7.3. Discussion: contributions and shortcomings

The indicative flood danger map for the city of Beni Mellal, along with the similar map designed by a joint study for the Fez urban agglomeration represent a pioneer achievement in Morocco. In this study we adapted the Swiss hazard mapping methodology that provides a comprehensive scheme for hazard identification, assessment and mitigation. Our approach provides several contributions to hazard assessment and further mitigation in the Moroccan context and is equally subject to inherent shortcomings.

7.3.1. Contributions

As stated above, this is a **pioneering work** in Morocco: to our knowledge only one pilot risk map project has been undertaken by the regional authorities of Al Hoceïma in order to address several risks (floods, landslides, earthquakes) in Morocco (IMS-RN 2011). The Al Hoceïma project is in a validation stage.

The indicative flood hazard map represents a sound **decision-making tool** that provides planners a comprehensive set of information related to the spatial imprint and consequences of floods threatening the concerned region. The additional flood magnitude and probability maps also provide information **transparency** related to the hazard map as well as decision criteria for further mitigation measures. For example, protection measures for specific sensitive locations (housing lots, institutions, etc.) can be oriented by the information provided by magnitude maps. Moreover, flood magnitude – frequency information is useful for designing alert and evacuation plans.

The indicative flood danger map is a **scientific document** that assesses hazard on the basis of quantitative measures (magnitude and probability). Unless risk assessment studies whose results are influenced by the definition of the highly qualitative concept of vulnerability, hazard assessment for mitigation measures provides planners with sound and transparent criteria for decision-making.

The Swiss hazard mapping procedure adapted in this study provides a set of **comprehensive planning prescriptions** based on scientific hazard assessment as well as sound options for addressing exposed communities' vulnerability to hazard. Indeed, danger zones gradually classify hazard in low, medium and high danger classes: additionally, each danger zone provides specific planning characteristics for risk mitigation (building prohibition, building regulation, hazard awareness-making). Within this study, the planning prescriptions stipulated in the Swiss method represent suggestions to planning and criteria for decision-making as no legal framework is available yet for their implementation in planning documents.

The indicative flood hazard map provides a basis for **re-thinking flood mitigation** strategies in the sense of the nation's recent commitment to the Hyogo Framework for Action goals. Currently in Morocco, hazard management relies mainly on active structural measures of flood protection, which are costly without providing full protection warranty. Moreover, some measures may induce the exposed communities a false sense of security towards flood hazard. As this chapter suggested, passive and active measures could be combined on the studied urban perimeter of Beni Mellal in order to sustainably mitigate flood hazard. Cost-effectiveness studies should be undertaken in order to assess the real costs and benefits of passive and active measures in an area exposed to floods like the studied Beni Mellal case.

By their **visual** characteristics, hazard maps provide the possibility for the public to acknowledge the spatial imprint and consequences of hazardous phenomena. These documents provide therefore local authorities sound awareness-making tools for hazard prevention and communities' responsibility involvement in the management process. Thus, local authorities should provide open-access to the cartographic documents and organize hazard acknowledgement campaigns.

Natural hazards in general and flood hazard in particular are a matter of **perception** (Thomi 2010), as the hazard concept is defined relative to the communities exposed to it. This chapter showed that hazard classification according to the Swiss hazard matrix corresponds to gradual hazard perception thresholds of hazard acknowledgment, active mitigation and intolerance. This may improve the hazard map acceptability area.

7.3.2. Shortcomings

The produced map is an indicative flood danger map, as its conclusions as well as the mapping precision were highly influenced by **uncertainty** related to the map's inputs. Indeed, scarce hydro-meteorological data resulted in hydrologic modelling uncertainty; further on, errors related to the existing elevation data influenced hydraulic modelling as well as the final cartographic document. To counterweigh this limitation, we used field derived-information to verify our results at each step of the indicative hazard map design. Yet, access to more precise data when available, would be an asset for better hazard predictions. Therefore we suggest data providers like the national weather agency (*Direction Nationale de la Météorologie*) should increase data accessibility for projects that concern hazard mitigation.

The Swiss danger map consists of a comprehensive hazard assessment and mitigation prescriptions structure. Unlike Switzerland, no **legal framework** is available in Morocco for integrating hazard assessment to planning documents. Therefore, this study's results represent suggestions for future planning and not effective flood hazard mitigation prescriptions.

The adaptation of the Swiss method to the Moroccan context consisted, among others, in modifying the hazard matrix probability thresholds. Data availability and the local hazard-related practice justified this choice. Nevertheless, this adaptation might overestimate the resulting danger class for medium to low frequency events. To compensate for this shortcoming, one could imagine using thresholds comparable to the Swiss ones or simply adapting the matrix to the Moroccan practice by modifying its structure.

Finally, the Swiss hazard matrix conception leaves relatively large freedom for hazard assessment by depicting danger degrees as matrix zones instead of matrix classes (see Figure 7.1). This could be considered as an advantage as well as a shortcoming for hazard assessment. Indeed, no clear prescription binds map designers in hazard classification. On the other hand, this structure provides a certain space for negotiation of hazard itself on a case-by-case basis, and of the danger map content when it is confronted to the public. We classified hazards so that we could partly remove the bias created by probability threshold modification.

7.3.3. Applicability of the method to similar contexts

In the light of the above-discussed results, we further consider the potential dissemination of the adapted Swiss approach to hazard assessment and mapping processes in similar socio-economical and environmental contexts.

First, we note that the Swiss hazard assessment and mapping method was only adapted for flood hazard assessment, using specific methodology related to this particular type of hazard. Indeed, the Swiss danger map method is applicable to other hazards (snow avalanches, landslides, rockfalls, and debris flows) and was designed in order to represent them synoptically on a single map document. For other hazard assessment or multi-hazard mapping, one should relate to the specific Swiss guidelines (e.g. OFF 1984, Lateltin 1997). Further adaptations to the chosen environment are to be expected.

The map document produced in this study is a hybrid map between the Swiss regional level hazard indication maps and the municipal level danger maps. In conditions of poor data availability or quality, we suggest that this hybrid approach is particularly suitable for assessing hazard and providing local authorities with scientifically informed, hazard-aware land-use recommendations. Yet, methodological limitations, data imprecisions and other factors of uncertainty need to be communicated to planners and the public, as hazard assessment implementation in risk management is subject to social negotiation.

An important aspect of hazard mapping dissemination and implementation is related to the public and institutional stakeholder's perception of the **map** and of the **hazard** this document depicts. Map perception is mostly related to its visual properties and the message it passes to the public (Fuchs et al. 2009). We shortly discussed the Swiss danger map colour code and its psychological implications for the public. Literature suggests the Swiss hazard matrix colour choice represents well certain risk perception thresholds (see Section 7.1.1), particularly in the flood hazard case. Experience in adapting the Swiss methodology to different contexts showed that in some situations, colour code adaptation was necessary to ensure map acceptance by the targeted public (SDC 2005). These adaptation efforts also proved that the probabilistic aspect of risk and hazard might highly influence hazard maps acceptance by the public and institutional stakeholders (SDC 2005). We suggest that mainstreaming hazard assessment is essential to map acceptance and further implementation.

Risk acceptance thresholds may prove to be crucial when adapting hazard assessment methodologies. For example, the 20-year return period flood might be perceived as very hazardous in Switzerland but can be seen as "rare" in a country such as Morocco, particularly when the probability concept behind this denomination is poorly understood. Therefore, hazard–related concepts need to be thoroughly communicated to stakeholders.

7.4. Conclusion

This section presented the final "product" of this study, the indicative flood hazard map for the piedmont urban agglomeration of Beni Mellal. This map assessed flood hazard according to the Swiss hazard map methodology, with certain adaptations.

Map results showed that for the three streams draining the city's central and northern part (Handak, Sabek and Aïn el Ghazi), maximum flood extent does not change considerably between different return period events. Therefore, a large part of this area was mapped as medium hazard, as frequent low intensity events are very likely to occur on the alluvial fan surface. For the Kikou stream, probability plays a more important role in hazard class definition. Two flood hazard patterns emerged: the upper alluvial fan reach is typically torrential and is defined by flood uncertainty, while the lower reach situated at the fan distal contact with the Tadla plain represents a transition towards more confined flooding patterns and is marked by relative buffering of the hazard zones.

The indicative hazard map represents a pioneering approach to hazard in Morroco. This scientific document provides planners with a decision tool for hazard mitigation by quantitative assessment of flood hazard on one hand and a comprehensive set of planning prescriptions on the other hand. The flood hazard indicative map designed within this project proved that hazard mitigation via hazard-aware planning is feasible for large areas within the urban context. This conclusion contradicts the present flood mitigation strategy adopted by the local authorities. The cost-effectiveness of different mitigation measures (passive or active) should be balanced in order to achieve the best-suited solutions to the flood hazard problem. Finally, the map is a useful tool for hazard acknowledgment by the public.

On the downside, the designed indicative flood hazard map is subject to uncertainties related to the hazard assessment inputs (hydrologic, hydraulic modelling) and precision losses due to the available cartographic data. Specific adaptations of the Swiss method might influence the final result. Finally, its implementation to planning is not regulated in Morocco; therefore, the map results can provide decision-making tools but cannot become significant in terms of regulation. Nevertheless, flood hazard management at the local level might integrate these results, as described in the further chapter concerning the current local management practice.

Dissemination of the method in similar contexts is dependent on input data quality and availability; therefore, strict extrapolation of the Swiss method might not be achieved. Hazard mapping implementation to risk management also depends on public and stakeholders perception of the map and the hazard concept it underlies.

In conclusion, this project’s final result provides hazard management in Morocco a comprehensive approach to hazard identification and assessment and a sound basis for further applications of this method in flood hazard mitigation activities.

8. From maps to planning

This project was thought as a knowledge transfer effort aimed at adapting the Swiss hazard assessment and mapping methodology to the Moroccan context. Since the Beni Mellal indicative danger map presented in the previous chapter represents the achievement of the methodological objective of this thesis, we discuss in this chapter the implications of actually implementing the cartographic document to risk management procedures. By implementation, we consider knowledge transfer via methodological adaptations on one hand, and the successful application of these adaptations at the local risk management level on the other hand. This chapter is divided into two parts. The first part portrays the actual risk management situation at the regional and local level in the study area from the point of view of institutional stakeholders and risk related institutions. The second part consists of a set of recommendations for local stakeholders. These recommendations reflect gained experience from the methodological adaptation. To do so, we follow two converging interpretation grids: the integrated risk management scheme that was theorized and applied throughout this work, and the knowledge management scheme that analyses our approach from the knowledge creation and transfer point of view (see Chapter 2).

In this chapter, we consider two types of knowledge processes: coding and sharing knowledge as best practice, and mapping existing internal expertise (Alavi & Leidner 2001). Knowledge networking (Alavi & Leidner 2001) is not accounted for in this project, even though this application is intensively used in the disaster risk reduction field (e.g. Mohanti et al. 2004, UNISDR 2013). We consider risk management actors and institutions with responsibilities within the studied area of Beni Mellal as forming one organization bound by the risk management and mitigation interest. In this context, we suggest that adapting the Swiss hazard assessment and mapping to the Moroccan natural and socio-economical context and the resulting recommendations consist of setting up a collection of **best practices** for further knowledge application in the risk management field. Moreover, the application of the Swiss hazard assessment and mapping methodology to a specific Moroccan location reflects an approach to know-how transfer by demonstration or "show-how" (Roberts 2000). That is, certain implicit knowledge can only be transmitted by demonstration. Then, exploring the risk management situation, the roles of actors and their specific area of expertise in risk management and reduction corresponds to **mapping** internal expertise within the above-defined "organization" (Alavi & Leidner 2001, see Chapter 2).

8.1. Institutional vulnerabilities in risk management

Risk is usually defined as a function of hazard and vulnerability (see Chapter 2). Vulnerability itself is a relatively fuzzy term (Birkmann 2006) resulting of unbalanced susceptibility and resilience in the hazard - exposed communities. As vulnerability is related to people, one can explore established relationships between actors engaged in the risk management process in order to assess the management's strengths and weaknesses. Institutional factors such as risk policies or risk management stakeholders may alter the vulnerability of communities in a number of ways (D'Ercole 1994, Dauphiné 2001, Alcantara-Ayala 2004, Lebel et al. 2006).

In our study case, the weight of institutions in risk management processes exceeds the roles of other stakeholders (e.g. the public or the insurance industry), possibly in relationship to the centralized character of the Moroccan state. Moreover, the relationships, roles and responsibilities of institutional stakeholders are expected to have a higher degree of codification than the public for example. Thus, conclusions drawn from this study could attain a certain level of generalization applicable to other study sites.

We therefore focus in this chapter on the very specific aspect of institutional vulnerability (Lebel et al. 2006), related to the way risk management (institutions and institutional actors engaged in the risk management process) in Beni Mellal increases or undermines the community's resilience to flood hazards. We define institutional vulnerability as the characteristics of the administrative and regulation system that prevent a better disaster risk management and therefore increase the overall community vulnerability. That is, institutional vulnerability is inversely proportional to the actual coping capacity the society builds through its institutions (Werren 2013).

Within this framework, we consider **institutional actors** (agencies, administration) separately from risk management **institutions** understood as rules or norms defining the roles, rights and responsibilities of risk management actors (Young 2002, Werren 2013). In order to assess the situation of risk management within the study area of Beni Mellal, we explore on one hand the existing institutions that regulate risk management, and on the other hand, the specific roles of institutional actors in risk management as well as the relationships they establish.

This chapter addresses institutional vulnerability form the point of view of potential hazard map implementation within the risk management strategies. Due to a lack of time and to its limited scope (assessing, mapping hazard and exploring potential map implementation to planning), this research is a preliminary draft with no pretention of covering the whole institutional vulnerability situation.

8.1.1. Mapping the management process

Preliminary mapping, regulation overview

Disaster risk management can be represented as a cyclic process around a reference event (OFPP 2003, Kienholz 2005, see Chapter 2). Thus, a given event triggers a response on the short term and recovery measures on the longer term. It also provides new experience and a basis for risk assessment in order to elaborate new mitigation measures for a better preparedness for the forthcoming events. We used the integrated risk management cycle as a "base map" to undertake the cartography of institutions, institutional actors, roles and relationships. By "cartography", we understand here to place the chosen elements (institutions and institutional actors) on the risk cycle according to their role in risk management, in order to better understand the dynamics of "who" does "what" in risk management in Beni Mellal and "how" actions are taken (Werren 2013). We also have an interest in "who" knows "what", that is, which capabilities exist in the risk management knowledge system. Before the field investigations, a preliminary cartography was undertaken, describing the expected roles actors and institutions play in the management cycle (Figure 8.1).

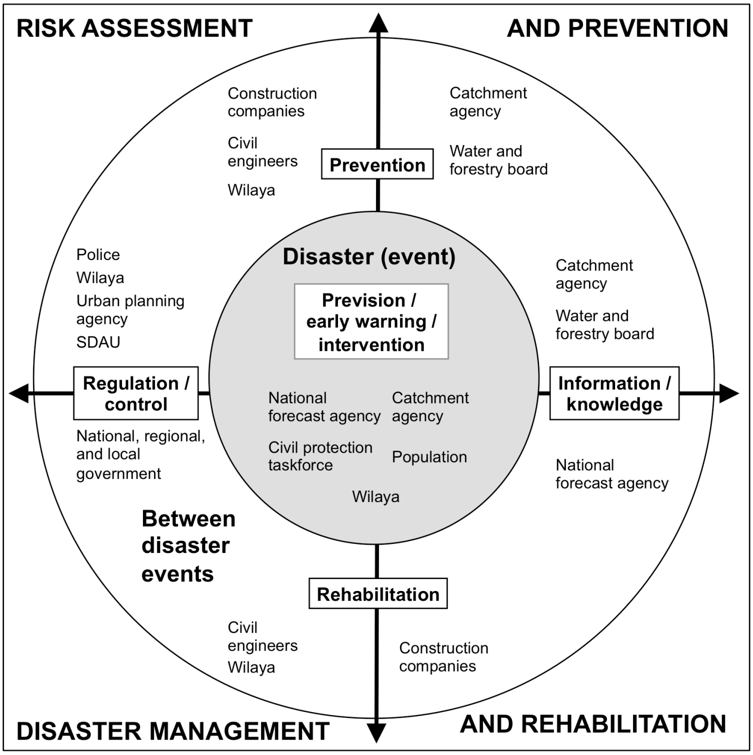


Figure 8.1. Preliminary "mapping" of institutional actors and institutions engaged in risk management in Beni Mellal.

The preliminary "mapping" was based on the field observations and contacts obtained during field surveys carried out in 2009 and 2010. This preliminary diagram contains also some institutions that were supposed to regulate relations between actors (e.g. S.D.A.U or *Schéma directeur de l'aménagement urbain* is a regional master plan for urban areas). As shown in Figure 8.1, some actors were expected to play multiple roles at different stages of the flood management process. An inventory of the current legislation was also carried out in order to outline the existing institutions or rules that frame the flood disaster management at the national and local level.

Interviews with institutional actors

The actors playing a major role in the flood disaster management, at the local and regional level, were selected and interviewed during a field survey carried out in October 2010. As Beni Mellal is the capital of the Tadla-Azilal region, many of the regional agencies are based here and are active in the management of flood disasters at the municipal level. Here is a list of the main actors:

- The “Wilaya” of the Tadla-Azilal region and the Beni Mellal province is the monarchy’s delegate at the regional level. It has a central role in steering and coordinating the other agencies’ actions;
- The Oum-Er-Rhbia Catchment Agency is a regional service created in 2002 following the 1995 Water Act, so as to shift water resource management from the regional to the catchment level. Its attributions encompass water resource management, especially through accumulation dams administration, and flood risk fighting. Two departments are active in risk reduction actions: the Studies department, responsible for hazard assessment via hydrological studies, and the Infrastructures department responsible of building flood protection structures.
- The Urban Planning Agency is mainly focused on urban planning at the Tadla-Azilal region level;
- The Water and Forestry Board is a regional agency in charge of the forests and catchment planning for flood protection: it covers the Tadla-Azilal region;
- The Municipality of Beni Mellal is concerned with all the aspects of urban development and administration;
- The Water distribution and sewage system (*RADEET*) is an autonomous agency managing the urban water fluxes at the city level;
- The State Secretary for Environment is a national agency responsible among others for the great water management infrastructures (water retention dams and dikes);
- The National Forecast Agency is in charge of the early warning during serious rainfall / flooding events.

The interviews were structured so as to address all the aspects of the flood disaster management cycle. In the whole, 9 interviews were carried out. Questions about regulation, active and passive mitigation measures, disaster management and post-disaster reconstruction were formulated (see Appendix 13 for a detailed interview example). The issue of “whom”, “what” and “how” actions are taken was considered. This helped finding out “where” on the risk cycle each actor actually stands and also which type of relationship (collaborative / hierarchical) the actors establish. Interviews also allowed developing an insight in the institutions (regulations and documents) that define relationships between and inside different agencies. Finally, a “map” of the flood management in the town of Beni Mellal was drawn (Figure 8.2)

8.1.2. Results and discussion

Institutions: current risk regulation

Flood risk management is directly addressed by the Water Act 10/1995, Section 20, that regulates the creation of Catchment Agencies whose attributions encompass the implementation of measures, gauging and hydrological and hydrogeological studies, for the quantitative and qualitative planning and water management and the setting up of the necessary infrastructure for flood prevention and protection. The Acts

10/1917 and 1/1969 decree the implementation of forest protection areas in order to avoid fluvial erosion and flooding.

No law concerning the urban areas contains any clear statement about the implementation of flood protection zones in cities. Nevertheless, protection areas are inventoried in urban Master Plans. In parallel the Public Hydraulic Domain was decreed by the 10/1995 Act, Section 1, as a buffer zone along the main rivers' banks (6m large) and all the other watercourses banks (2m large). This specification is highly dependent on how Catchment agencies define riverbanks: depending on the situation, they can represent the outer limit of a floodplain or the outer limit of the main river channel. Usually in cities land use pressure and economic interests push the Public Hydraulic Domain closer to the river channels, invalidating its flood protection role (oral information).

National, respectively regional Master Plans and Programs generally embody the Water Act's general specifications. At the local level, most of the "institutions" regulating flood risk management are semi-formal agreements between different Agencies. Internally, circular letters and specifications regulate Agencies' behaviour and actions at different stages of the management process.

The Moroccan legal framework is, in conclusion, not yet developed to support an integrated risk management approach. The lack of a legal basis can hinder the implementation of danger maps, unless decision-making in the land use field is undertaken at the community level (Zimmermann et al. 2005). In the presence or absence of an adequate legal framework, nevertheless, institutional and non-institutional actors play an important role in developing risk mitigation strategies (Alcántara-Ayala 2004, Reynard et al. 2008).

Risk management in Beni Mellal: institutional actors, their relationships and system weaknesses

The interviews with institutional actors involved in risk management in Beni Mellal allowed us to outline the management process, including the involvement of the different actors and the type of relationships they carry on (Figure 8.2). The sketch highlights the primary role undertaken by the Wilaya as a coordinator and "pilot" of almost all actions. Indeed, this actor beacons prevention, intervention and reconstruction actions, sometimes in an organized and official way (e.g. the disaster intervention plan ORSEC presented further on) or in an implicit manner as it represents the central power of the King at the regional level. This role is regulated through a regional Risk Commission led by the Wilaya and comprising all the agencies (oral information).

The important role of the Wilaya reflects the centralized Moroccan political system, implying a top-down risk management system at the institutional level. This study did not allow drafting the flood risk management in the larger frame that would include the population touched, but it gives us a glimpse on the type of relationships settled. One could argue that community-based risk mitigation approaches might be hindered by such a top-down system.

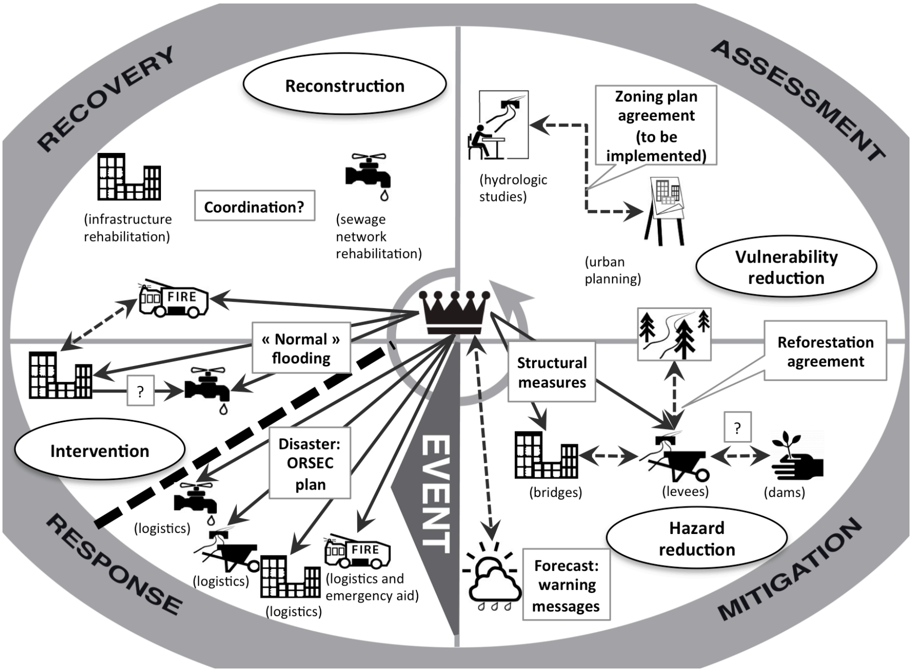


Figure 8.2. Institutional actors within the risk management cycle. Symbols are detailed below.

Urban Planning Agency	Municipality
Catchment Agency (Studies Department)	Water distribution and sewage system
Wilaya (King's representative)	Civil Protection Taskforce
State Secretary for the Environment	Regional Forestry and Surface Water Board
Catchment Agency (Infrastructures)	Collaborative relationship
National Forecast Agency	Hierarchical relationship

A second insight focuses to the uneven distribution of actors and actions among the risk stages cycle. Indeed, actions aimed at vulnerability reduction are minimal or at a planning stage. That is, an informal agreement relating the Catchment Agency and the Urban Planning Agency states that the results of hydrological studies led by the former should be integrated in further Zoning Plans developed by the latter (oral information).

The "map" we created (Figure 8.2) shows clearly the emphasis set on structural measures, aimed at hazard reduction, but also the complexity of relationships among actors at this level. That can be explained by the costs of the infrastructures needed to protect the urban areas, so that several "donors" build specific objects (dams, levees, bridges). At the same time, these scattered actions induce timing problems: for example, once levees were built by the Catchment Agency, roads crossing the rivers have blocked floodwaters, because bridges were not elevated at the same rate.

The emphasis on one type of risk mitigation approach (i.e. active measures) contradicts the principles of an integrated risk management approach. Nevertheless, the protection-based risk mitigation approach, enforced in the current Moroccan risk policies, reflects a historical development that could be traced in other countries. For instance, awareness about the inefficiency of sole active protection measures arose relatively recently in a country with a long flood risk management history such as Switzerland (Lüthi 2004, Reynard et al. 2008)

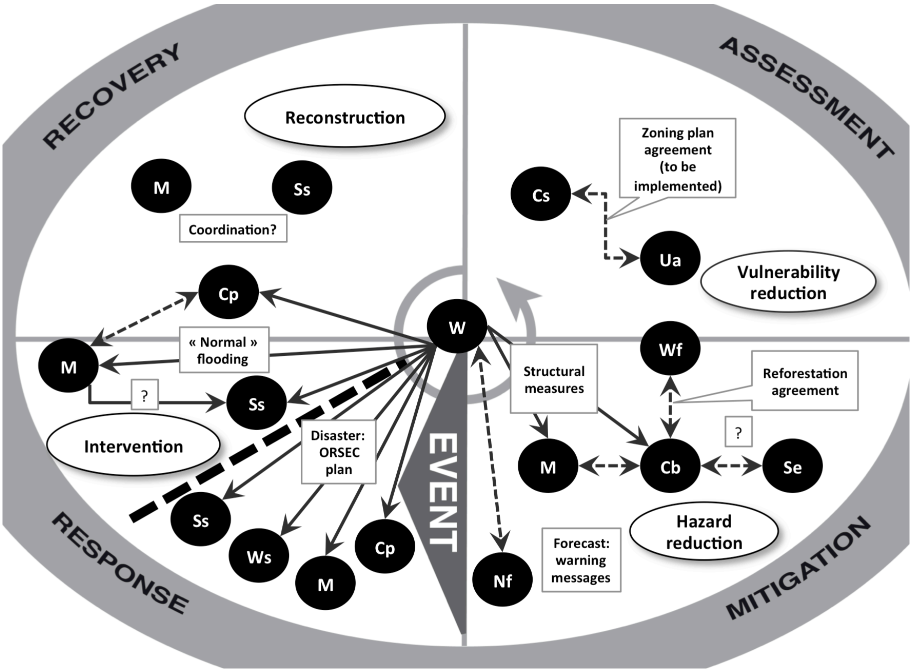


Figure 8.3. The institutional actors and their relationships. Cs: Catchment Agency (Studies); Cb: Catchment Agency (building); UA (Urban Agency); WF: Regional Forestry and Surface Water Board; M: Municipality; Nf: National Forecast Agency; Cp: Civil Protection Taskforce; Ss: Water distribution and sewage system; Se: State Secretary for Environment; W: Wilaya. For relationship typology, see Figure 8.2.

With respect to flood response, the concerned actors described two situations. First, when a "disaster" declares, the Wilaya launches the ORSEC Plan involving all the Agencies, which are expected to provide their logistics and skills. The ORSEC plan (Plan d'*organisation des secours*), is an emergency intervention plan that operates when a natural, technological or terrorist disaster is declared. The ORSEC plan is organized around two control stations: a fixed one located at the Wilaya, and a mobile one led by the Civil Protection commander. All the actors involved have clear responsibilities during the crisis. The Civil Protection represents the main intervention task force. The operations are led directly by the Wali (Prefect), by means of the fixed control station. Second, and most common, is the "normal flood" situation where responsibilities are less specified. The Wilaya holds a coordinating role. The delimitation between "disastrous" and "normal" floods is political, as it depends on the Wali's decision. No ORSEC plan was declared in Beni Mellal following a flood event; therefore, the "normal" flood intervention pattern prevails.

Poorer organization in the response phase, as outlined by the interviews (and rendered in Figure 8.2 and Figure 8.3) might reflect a loose demarcation of intervention roles for the actors involved, compensated at the decisional level by the Wilaya's steering role, consistent with the top-down management pattern we described earlier. In crisis situations, it has been proven that the intervention efficiency can be strongly influenced by the designation of roles actors should play: role confusion, lack of communication between actors, or the lack of willingness to achieve the required intervention tasks may severely hinder the response process (Reynard et al. 2008, Thomi 2010).

The process of rehabilitation is the least regulated (Figure 8.3). The interviewed actors highlighted no specific coordination in the reconstruction effort. The Municipality, as an end beneficiary, must rebuild the damaged infrastructure. It should be noted that protection objects have a warranty time of one year only and that later damage is completely at the Municipality's charge. The Water distribution Agency is the only actor to benefit of the insurance system. Finally, the rehabilitation is dependent on the regional or local budget and most actions are taken on a priority / emergency basis. The Civil Protection is assumed to play a role in the early rehabilitation process as an emergency aid agent, but does not engage in long-term reconstruction actions (oral information).

Rehabilitation measures play a central role in decreasing community vulnerability: at this stage, actions must be taken to restore the community functions and to avoid creating new risks (SDC 2008). The lack of regulation during the rehabilitation stage may therefore negatively impact a community's resilience to further flood events.

Finally, some actors play complex roles: on one hand they are active at different stages of the risk cycle, on the other hand, they can be in a hierarchical / collaborative relationship with other actors (e.g. the Catchment Agency develops autonomous agreements with other Agencies but is subject to the Wilaya through a direct hierarchic relationship). Figure 8.3 stresses the relationships between actors and the "institutions" regulating them. It also highlights the variability of focus on the different stages of the risk cycle. Less descriptive, this "map" offers a better insight on the system's dynamic.

Risk management integration depends on the way actors' roles, and their respective interactions, are delimited and coordinated. Actors playing multiple, complex roles, as well as the confusion between hierarchical levels of the management process might make the difference between a flood event and a disaster (Thomi 2010). This state of fact reminds the complexity paradigm (Smith & Petley 2009) in that a disaster results from complex interactions between multiple variables (e.g. natural phenomenon, infrastructures quality, timing of the event, socio-economic categories of threatened people). Therefore, by integrating risk management, i.e. by organizing the community's resilience to hazards, the outcome of the complex natural and anthropic system called natural disaster can become more predictable and risk can be mitigated on the long term.

8.2. Institutional risk management from a knowledge management perspective

In the previous section we gave an answer to questions about "who" does "what" in risk management in Beni Mellal and "how" actions are taken from a relational point of view. We like to explore here the issue of "who" knows "what" in risk management in Beni Mellal, that is, which type of knowledge is available and how knowledge is used within the risk management "organization". In terms of knowledge management, we draw a **map of the internal expertise** (Alavi & Leidner 2001) within this "organization". A knowledge inventory can become a sound tool for auto-evaluation (Werren 2013) of the risk management process that can open new perspectives for better use of the existing knowledge and for the creation of new knowledge assets.

8.2.1. Actors as risk knowledge pools

Some of the questions addressed to institutional actors during the 2010 survey referred to risk as a concept and to risk perception (Appendix 13). Respondents provided partial definitions of risk that emphasised one or another aspect of the concept: threat, probability of occurrence, losses, or the notion of threshold, which is related to the risk acceptability sphere. The risk evolution in time is perceived along sectorial aspects too: for example, the Forest and Surface Water board considers catchment degradation and urbanization as a cause for risk increase, while the Catchment agency draws the risk assessment problem meaning that risk did not change but risk assessments are out of date.

This fragmentary approach to the notion of risk is somehow diagnostic of the way flood risk management runs in Beni Mellal. Indeed, the actors intervening in risk management form an ad-hoc organization of sectorial knowledge pools that lack effective networking. Moreover, inside the same institution, different departments contain sectorial sets of knowledge that trigger sectorial responsibilities in a well defined internal hierarchy. For example, the Studies and Infrastructures departments within the Catchment agency address questions strictly related to their field of expertise and reject to share opinions on the other department's field.

Hierarchy seems to play an important role in risk management generally and in the definition of specific tasks for the involved actors. The Civil Protection taskforce represents a good example in this sense. Indeed, this unit with a military hierarchy intervenes in risk management only in pre-established routines (ORSEC plan for example) or at the Wali's order and for well-defined tasks. Civil protection represents a distinct pool of knowledge (intervention and rescue routines, evacuation plans) that designates it more as a tool for risk management than an actor.

Most of the actors found it difficult to assess their own knowledge on risks; yet, during interviews specific capabilities could be delimited. Most of the actors hold specific scientific or technical knowledge (hydrologic, building and hydraulic engineering, forestry, etc.) Some develop legal knowledge mostly related to the urban aspects of planning (for example the Urban Agency or the municipality of Beni Mellal) while others develop the coordination role (mainly the Wilaya). Finally, experience-based knowledge such as the Civil Protection’s intervention and evacuation routines interact with the other sectorial knowledge pools.

Within this context, the legal framework related to risk issues, which we consider as shared knowledge, was explored. Each actor reported those laws and directives that directly regulate their own activities, so that no broad vision on risk management could be deducted.

A similar fragmentary image resulted from inquiry into the passive mitigation measures and the importance of planning in the risk management process. Actors focussed on urban aspects (Urban Agency, Beni Mellal municipality, Sewage system) were familiar with regional and local master plans while the other actors ignored their importance for risk management or their own activities. Several confusions related to master plans and risk management could be observed: indeed, several actors reported flood-prone zones as included to urban plans as non-building areas, which is not legally true, as no legal framework exists for implementing flood zones to planning. This confusion could result from the intersection of the Public Hydraulic Domain with master plans; in this case, the streambed and the 2m buffer required by the Water Act is indeed marked on the urban plan, but flooding zones are more extensive than the legally enforced Public Hydraulic Domain.

Fragmentary, incomplete or even erroneous knowledge on risk can impact the risk management quality (Reynard et al. 2008, Thomi 2010). Moreover, in a context of weak system organization, compensated by the leading role of one actor, managing sectorial knowledge and practice may become a challenging task.

8.2.2. Knowledge fluxes within the risk management “organization”

The analysis of institutional actors’ role in risk management, as depicted in Section 8.1.2 showed that actions are generally taken in a top-down logic, as the royal representative in the region (Wilaya) is the leader and coordinator in all situations. Yet, the top-down management is in certain cases replaced by informal collaboration between the actors involved, which lead to innovative approaches to risk management. One could delineate two types of knowledge fluxes that lead to effective solutions in risk management: collaboration **between actors** (Werren 2013) and collaboration with **external knowledge pools** (practitioners and the academics) Figure 8.4 exemplifies knowledge fluxes established in flood prevention.

Collaboration between actors

Awareness about the importance of catchment conditions upstream of the city in flood development and aggravation resulted in an informal agreement between the regional Forest and Surface Water board and the Oum-er-Rhbia Catchment Agency that aims at fighting catchment erosion and decreasing runoff by a series of catchment restoration measures, mostly within the Handak catchment. The Forest and Water Surface board undertook reforestation measures in the most sensitive catchment zones while the Catchment Agency built several flood control and slope stabilization structures along the most torrential streams.

This agreement overstepped the usual hierarchy by bonding two risk management actors on a collaboration basis that allowed bringing an innovative solution for better flood control in the city of Beni Mellal (Figure 8.4). The semi-formal agreement is, in our sense, innovative, as it tends to solve flood risk problems with a holistic view of the hydrological risk situation. Indeed, by acting on the upstream catchments, these measures aimed at mitigating flood risk in the fast-growing Beni Mellal urban perimeter.

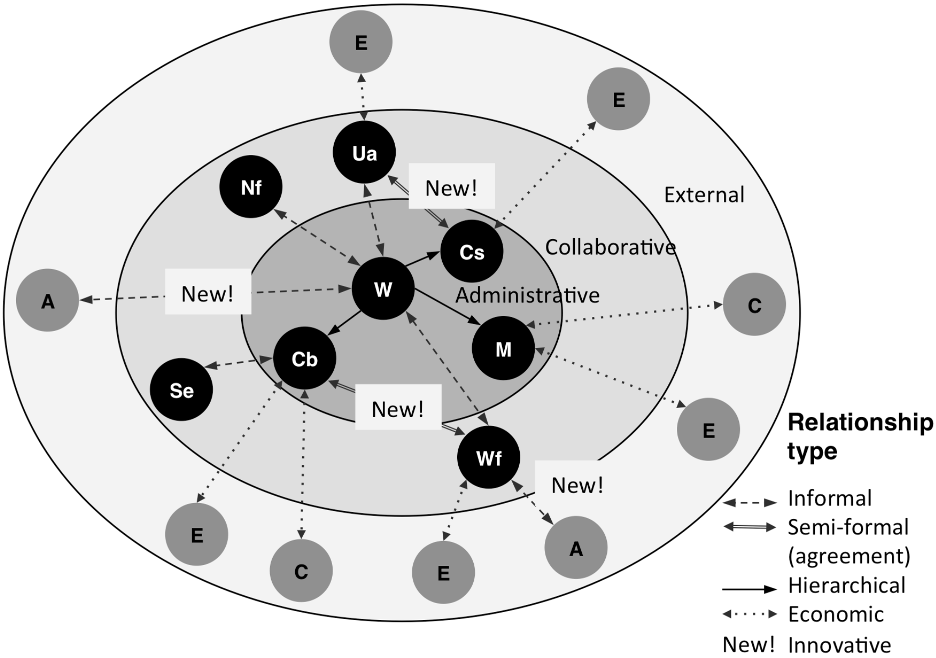


Figure 8.4. Risk prevention: interactions among actors and between the management "organization" and external knowledge pools. Emphasis on innovative knowledge interactions. Cs: Catchment Agency (Studies); Cb: Catchment Agency (building); UA (Urban Agency); Wf: Regional Forestry and Surface Water Board; M: Municipality; Nf: National Forecast Agency; Se: State Secretary for Environment; W: Wilaya; E: engineering firms; C: construction firms; A: academia.

Likely, an agreement between the Catchment Agency and the Beni Mellal regional Urban Agency aims at introducing the Catchment Agency's hydraulic studies results (e.g. maximum flooded area for a given event) within future urban and rural master plans in the Beni Mellal province. This agreement could successfully fill the legal gap between risk management and planning by taking into account scientific hazard assessments in the planning process. However, in practice, one could notice also shortcomings to this possible success story of horizontal collaboration. First, the modalities for implementing the hazard assessment to urban and rural plans were not well defined, the simplest solution being to classify for example the 100-year maximum flood extent as an unconstructible zone. Second, there were timing problems between the agencies, in that the Urban Agency mandated hydraulic studies for new urban and rural plans short before the plan publication, letting little time to the Catchment Agency to actually produce those studies (oral information). This collaboration example reveals that the missing legal framework for planning implementation to risk management strategies can be compensated at the community level (Zimmermann et al. 2005); nevertheless, the agreement will only be effective if the actors involved clarify the content and timing of their exchanges.

Collaboration with external knowledge pools

The risk management actors in Beni Mellal rely on external knowledge pools in their activities. Indeed, most of the studies, surveys and technical work are delegated to external engineering firms (Figure 8.4). This allows agencies to alleviate their needs in infrastructure and expert personnel while accessing well-established scientific and technical knowledge. Yet, the actors seem less open to innovations stemming in the academic world. That is, most of the relationships they take with the academia are limited to offering students training ground and an insight to the professional world.

One notable exception to this state of fact relates to the collaboration between several actors (municipality, Civil Protection) and the technical university in Beni Mellal in assessing cavity collapse risks within the city’s historical centre (*medina*). The densely populated *medina* of Beni Mellal is built on travertine series that undergo active karst processes resulting in numerous cavities that threaten to collapse (El Khalki et al. 2005). Mapping the cavities required pioneering techniques such as geo-radar measurements (Najine et al. 2006), probably not available by engineering firms. In the same line, Civil Protection and the Forest and Surface Water board reported to collaborate with the academic milieu in wildfire risk assessment (oral information). One may conclude that the academics could offer opportunities for innovation in risk assessment for further management tasks (Figure 8.4). Nevertheless, their attractiveness is still limited for institutional actors in risk management.

We suggest that the present study embodies a good example on how the academic world can provide key knowledge for risk management strategies. This study adapted a well-established hazard assessment and mapping methodology to a specific Moroccan location, using a multi-disciplinary approach and researching for the best-suitable adaptations in the given context. By doing so, this study achieved to integrate a set of scientific, practical, institutional, and political insights related to risk management. The integration capacity of academic studies needs to be accounted for in risk management as it represents an important asset for further innovation.

8.3. Recommendations: hazard assessment and implementation

Adaptation of the Swiss hazard assessment and mapping method to the specific context of Beni Mellal allowed us to gather insights and experience that need to be communicated for further dissemination of hazard assessment in similar settings. By inquiring on risk management situation at the institutional level in the region, we could assess the present risk management functioning, its strengths and weaknesses, and thus set hazard assessment and mapping in a context of potential implementation. The conclusions we drew during this study crystallized in a set of recommendations to local authorities, planners and hazard assessment practitioners (see Reynard et al. 2012 for recommendations related to the whole project). We present the recommendations according to this study's objectives: applied, methodological and institutional. In the sense of know-how transfer approaches, the recommendations we draw below represent a set of **best practice** insights stemming of the applied aspect of this study. Methodological recommendations refer mostly to the hazard assessment and mapping method adaptation, whereas institutional recommendations envisage hazard assessment implementation within an integrated risk management approach. A summary of these recommendations is available in table form in Appendix 14.

8.3.1. General methodological recommendations

These recommendations refer to all the elements necessary for correctly assessing flood hazard in similar situations in Morocco: context, data, and technical approaches. The assessment of other hazards needs particular adaptations that were not addressed in the present study.

- **Quality input data** is essential for correctly assessing hazard. In this sense hydro-meteorological data scarcity represented an important challenge when modelling catchment hydrological behaviour in the Beni Mellal study area. Therefore, it is essential to establish **hydro-climatic databases**. Moreover, it is necessary for the Moroccan authorities to densify their **gauging networks**, especially in mountain-plain interface regions such as Beni Mellal.
- Local planners and local and national authorities should endeavour to produce good quality and precise **Digital Terrain Models** (DTM), at least within the urbanized areas. Topographic data represents the basis for hydraulic models but also for the cartographic rendering of assessed hazards: danger map implementation requires precise cartography within the analysed perimeter.
- **Data availability** may also represent an important problem when assessing hazards: indeed, data might exist but it is not made available or is too costly. We recommend therefore that the main data providers (National Forecast Agency, Catchment agencies, Urban agencies, etc.) provide the needed data **free of charge** for research purposes or for risk management strategies.
- When assessing hazards related to floods, a set of multidisciplinary skills are needed. The hydro-geomorphologist's, hydrologist's and hydraulics engineer's expertise as well as cartographic skills need to be combined in a **holistic**

approach to hazard assessment. Obviously, several experts with **sectorial skills** need to work together and more importantly **communicate** their results within the hazard assessment process. We emphasize here the interest in involving geomorphologists and their **field expertise** to the process as hazard assessment requires accounting for the field dimension of hazard.

- In order to obtain comparable hazard assessment results within a territory, methodologies should be **unified**, for example by providing **guidelines** to hazard assessment practitioners. Cartographic choices, hazard thresholds and hazard assessment standards should be defined in a uniform manner throughout the assessed territory.
- Within uniform hazard assessment standards, practitioners should nonetheless be able to **adapt** their approach to the **context** of their study site. The choice of models, calibration modalities, and the importance of geomorphic mapping in final assessment are to be adapted to the chosen territory and its hydro-geomorphic conditions.

Data quality and availability, as well as the required, often multidisciplinary skills, represent challenges as important as the lack of a legal framework when it comes to producing and implementing danger maps (Zimmermann et al. 2005). This study showed that a relatively close adaptation of the Swiss methodology for flood hazard assessment and mapping is possible in conditions of scarce data.

8.3.2. Specific methodological recommendations

We gathered useful insights on hazard assessment and mapping adaptation during each process stage: geomorphic mapping, hydrological and hydraulic flood modelling, and indicative danger map design.

Hydro-geomorphic mapping: the phenomena map

- Hydro-geomorphic mapping may prove to be **time-consuming**, requiring therefore **guidelines** focussed on the essential aspects a hydro-geomorphic field survey should reveal. Geomorphologists should concentrate on those elements essential for the comprehension of hydro-geomorphic behaviours, hazard magnitude as recorded in landforms, and optionally the verification of model accuracy on field.
- The cartographic adaptation of the Swiss method for *phenomena* mapping should be **uniform** throughout the assessed territory. This study proved it to be a challenge to render uniformly hydro-geomorphic realities in different locations (see Reynard et al. 2013, for the methodological issues and Lasri 2013 for insights on the joint Fez project). We recommend using the principle of the Swiss adaptable *phenomena* map (Kienholz & Krummenacher 1995) in order to achieve a certain degree of uniformity in mapping.

Hydrological flood modelling

- In scarce hydro-meteorological data conditions similar to this study's site, thorough **catchment knowledge** represents an important asset in correctly modelling hydrological behaviour. We recommend therefore that hydrologists acquire knowledge about catchment land use, geology, soil cover, vegetation, and geomorphic aspects using cartographic material, airborne imagery and field surveys. Obviously, communication with other experts (e.g. geomorphologists) is essential.
- Field surveys can serve also for **verifying model results**; therefore, hydrologists should use the ***phenomena*** map as it represents an important basis for confronting model results to the ground reality.
- Hydrologic models need to be **adapted** to the hydro-climatic context and data availability, according to the parsimony principle. Nevertheless, when catchment knowledge is sufficient, practitioners should avoid the most parsimonious models (e.g. empirical equations) and endeavour to render the catchment's hydrological behaviour in a satisfying manner.
- Finally, when modelling hypothetical flood events based on the probability principle, hydrologists should account for the difference between **rainfall** and **flood recurrence period**, and more importantly they should communicate this difference to risk management stakeholders.

Hydraulic flood modelling

- Hydraulic flood modelling is essential for assessing flood hazard, in terms of spatial and dynamic flood development. For correct hazard assessment, we recommend that models should be **adapted** to the type of **hydraulic behaviour** to be assessed: 1D models run well in river valley flooding situations while 2D models are necessary for modelling unconfined flows on complex topography such as alluvial fans; steady flow models simulate well slowly propagating floods, whereas unsteady-flow models are more suitable for fast-propagating flash floods.
- **Ground data** is essential for calibrating hydraulic models; in addition to field surveys and the ***phenomena*** map, flood extent data for model verification could be also extracted from **airborne imagery**.
- Hydraulic models may be **costly**. We recommend undertaking a **cost-effectiveness** analysis when choosing a model. One should account for the available data, field configuration and the desired assessment precision in balance with the necessary financial investment.

Indicative danger map design

- The final product of hazard assessment and mapping according to the Swiss methodology, the danger map, represents a technical assessment document resulting from the previously described stages. This document also contains all the **uncertainties** accumulated during these stages. Therefore, the precision of the resulting danger or indicative danger map is a function of all input data quality and precision. We recommend that in situations similar to the Beni Mellal case, where data scarcity represents a real challenge to hazard assessment, the final product should be an **"indicative"** document, i.e. a decision-making tool for further risk-aware planning.

- In this study, we did not explore map perception by the public. We nonetheless recommend testing the **visual adaptation** of the Swiss danger map to the public, when disseminating this method to broader territories and implementing it to risk management strategies.
- In the same line, map and **risk acceptability** needs to be tested before implementing the cartographic document: one should comprehend what represents "acceptable" risk for the community and for the public authorities.
- Danger maps contain **abstract concepts** like **risk** and **probability** of occurrence that need to be **communicated** and explained to the public as well as to risk management stakeholders in order to enhance map acceptability. Information gatherings, workshops, radio information and other means of communication should be established for informing communities on risk issues.
- Finally, unitary **guidelines** for designing danger maps are to be produced, published and implemented in order to obtain comparable assessments and uniformly plan risk mitigation over the chosen territory.

(Indicative) danger maps present an amount of uncertainty related to data inputs and the different stages of the map design. This uncertainty becomes problematic when the map takes a political aspect, i.e. when implemented in planning documents (Thomi 2010) with territorial and land use consequences. This uncertainty must be assessed, and further communicated within the management process.

8.3.3. General institutional recommendations

Hazard assessment and danger maps represent primarily decision-making tools, as they are not legally enforced. Their findings become binding for planners and the population only when implemented to planning documents (Penelas et al. 2008). In Morocco, the link between hazard assessment and planning is still inexistent and risk management has not reached yet the "integrated" aspect presented throughout this study. We draw below a set of recommendations related to the implementation of hazard assessment to mapping on one hand, and to risk management integration on the other hand.

- Morocco needs to develop a **legal framework** that accounts for and promotes **passive risk mitigation measures**, as risk is presently only addressed using structural protection measures. This framework should on one hand establish hazard assessment and mapping as **compulsory** for local communities, and on the other hand enforce hazard maps implementation to planning.

- Moreover, Morocco should actively involve in **generalizing hazard assessment and mapping** to the entire territory, ideally following unitary guidelines for hazard assessment and uniform cartographic rendering.
- The importance of urban planning in mitigating risks by decreasing exposure needs to be translated into active efforts for **controlling urban sprawl** in hazard exposed areas. Building codes require, therefore, taking into account risk issues, while building prohibition in exposed areas needs to be enforced.
- This case study revealed the relative lack of integration in risk management at the institutional level in Beni Mellal; yet, the inquiry on institutional actors' roles and relationships represents a valuable **self-assessment tool** that can identify inherent vulnerabilities, enhance coordination and help developing integrated risk management (Werren 2013). Similar inquiries should be used in order to diagnose the situation in risk management in order to improve risk mitigation capacities.

8.3.4. Specific institutional recommendations

These recommendations result directly of our experience with institutional risk management actors in Beni Mellal; their application can nevertheless span more generally to risk management in Morocco.

- The case study in Beni Mellal revealed the **unbalanced** involvement of **actors** and **actions** on the risk cycle, resulting in the overestimation of active risk mitigation measures. In a context of fast and uncontrolled urbanization, local planners and risk mitigation actors need to address passive risk mitigation measures as a priority of their mission.
- Beni Mellal offers a good example of fast spreading urbanization in exposed areas. Local authorities are therefore required to **control the building pace** in hazardous zones such as the alluvial fan apex on Sabek and Handak streams.
- The bond between **hazard assessment** and **planning** needs to be reconsidered in order to obtain efficient risk mitigation measures. Indeed, an agreement between actors aims at transferring hazard assessment to urban and master plans in the Beni Mellal region; nonetheless, this convention was not sufficiently enforced at the moment of the survey (October 2010). For efficiency, we suggest conventions between actors should receive certain legal basis, at the province level for example.
- This case study also revealed a need for **coordination** between actors and their responsibilities in undertaking **active protection measures** in order to avoid timing problems with hazardous consequences on the community.
- Field surveys in Beni Mellal showed that the construction of certain hazard

mitigation structures (flood reduction dams for example) resulted in increased slope erosion and important sediment mobilization, with direct consequences on flood hazard. Authorities in charge need to address **mitigation measures' side effects** and coordinate their actions in order to avoid replacing one problem with another.

- **Coordination** is also needed in dealing with **"normal" flood situations** at the institutional level. Indeed, actors should better acknowledge their respective roles and responsibilities in these situations in order to replace the present ad-hoc intervention mode.
- There is a need to **rethink the rehabilitation stage** by defining roles and resources (e.g. setting a budget) in order to unburden the Municipality in reconstruction situations.

Most of these recommendations envisage a better integration of risk management in the sense of a "risk cycle" (Kienholz 2005). Balancing the different stages of mitigation, response and recovery, and acknowledging the importance of vulnerability triggers such as uncontrolled urbanization are expected to reduce flood risks in a given community.

A set of recommendations result from our analysis of risk mitigation in a knowledge management perspective. We present them below.

- Risk managers need to hold an uniform set of knowledge related to risk conceptualization, integrated risk management, the importance of passive and active measures in risk mitigation, and more. They equally need to comprehend the legal framework regulating risk management in all its aspects and thus acquire a broader vision on management potentials. Workshops, guidelines, Internet platforms and other types of information should be produced in order to **educate** actors to **integrated risk management**.
- This study concluded that most of the actions in risk management in Beni Mellal follow a **top-down** logic. We suggest that hierarchy could be used as a **catalyser** in risk management by clearly defining roles and responsibilities of each actor at all stages of the management process.
- Thus, informal **agreements**, that proved to bring innovative and more integrative solutions for mitigating risk, should be **formalized** by a clear definition of responsibilities, timing, and routines.
- Risk management actors represent **sectorial knowledge pools**. In an integrated management perspective, they need to **bridge** their **skills** and **communicate** risk management issues among actors, and to the public.
- Finally, risk management should open to **external knowledge pools** (such as the academic world) that could provide innovative solutions in risk mitigation.

Risk management is based on knowledge: fragmentary or erroneous knowledge has, therefore, a great impact on its quality (Thomi 2010). This study showed how sectorial knowledge can be shared using semi-formal agreements between actors or collaboration with external knowledge pools in order to provide new risk mitigation solutions. Likely, sectorial knowledge use and decision-making can have a negative impact on the risk management process.

9. Conclusion

9.1. Concluding outline

Uncontrolled urbanization and new climatic trends have increased communities' exposure to flood hazards in urban areas set on mountainous outskirts in Morocco. In order to mitigate this emergent risk, hazard assessment and mapping set the basis for hazard-aware planning and control of the urbanization pace. Planning strategies, or passive mitigation measures, prove to be more efficient than sole structural protection measures, as they aim at increasing communities' resilience to hazard. This study was mandated by the Swiss agency for Development and Cooperation (SDC) in a context of knowledge transfer and cooperation. It aimed at adapting the well-established Swiss method for hazard assessment and mapping to the piedmont city of Beni Mellal, capital of the Tadla-Azilal region in Morocco. The indicative danger map, our final "product", stems of methodological adaptations of the Swiss method to hydro-climatic, morphologic and practical conditions specific to the studied area. The potential implementation of the indicative danger map to planning strategies was equally explored in a contextual study of the present risk management conditions at the institutional level in order to identify vulnerability triggers and potential management integration.

In this study we followed relatively closely the Swiss hazard assessment and mapping method. Successive surveys in 2009 and 2010 provided the basis for detailed hydro-geomorphic mapping that resulted in an adaptation of the Swiss *phenomena* map containing all those elements (natural and anthropic) related to flood development and aggravation in the city of Beni Mellal (Reynard et al. 2011). Field surveys also provided the basis for further model verification by mapping known flood event spatial extent and estimating peak flood discharges along selected stream cross-sections.

In order to comprehend the hydrological behaviour of the four catchments that drain the city of Beni Mellal and often produce inundations, we performed hydrological modelling of two rainfall events followed by flooding that occurred during the survey period (in February 2010 and October 2010). Model results were verified using field-collected data. The established hydrological model was then applied to hypothetical 20, 50, and 100-year rainfall events, in order to obtain flood hydrographs corresponding to high, medium and low probability flood events.

Flood hazard assessment is primarily based on model computations related to the potential maximum spatial extent of given return-period floods as well as their intensity in terms of maximum water depth and / or flow velocity). As reference events are rarely field-monitored, we first modelled one known flood event (October 2010) that could be verified with field-collected data. The established model was then run using the previously obtained 20, 50, and 100-year flood hydrographs in a 2-dimensional hydraulic model, suited for complex topographies such as the alluvial fans of the Beni Mellal study site. We obtained two types of maps: flood intensity maps (maximum water depth and flow velocity) and flood probability maps (maximum flood extent for high, medium and low probability flood events).

Flood intensity and probability maps were crossed using the Swiss hazard Intensity / Probability matrix to obtain the indicative danger map according to the Swiss methodology.

The indicative danger map is a technical, scientific document and a decision-making tool for risk management stakeholders. Its findings can only become effective if they are implemented and thus enforced in planning documents. The potential for danger map implementation was explored in a contextual study referring to risk management situation at the institutional level. Institutional vulnerability was assessed, together with institutional actors' roles and interactions within the context of integrated risk management. Roles and interactions were equally explored from a knowledge management perspective in order to identify those interactions that potentially provide innovative solutions for risk management. Finally, a set of recommendations for risk management stakeholders was drawn, stemming from the methodological adaptation of the Swiss method as well as from institutional risk management exploration.

9.2. Back to the problem

This study was built around three main objectives: a methodological one aiming to adapt the Swiss method for hazard assessment and mapping in a specific Moroccan context, an institutional exploration of the potentials for indicative danger maps implementation in risk management in Morocco, and a more general applied research objective, aiming at transferring knowledge, be it conceptual or institutional. Throughout this research we sought answers to the basic questioning these three research axes proposed. In the next section we provide answers to these questions, as they result from the study.

9.2.1. Methodological objective

The degree of adaptation of the Swiss hazard assessment method to a Moroccan site is dependent on two important variables: the environment and the available data. Throughout this study we gathered insights to answer the base questions.

1) Which adaptations are necessary to transpose the Swiss hazard assessment method developed in a temperate country to the semi-arid piedmonts environment?

Semi-arid environments reveal typical hydro-climatic and hydro-geomorphic forms and behaviour resulting from marked seasonal contrasts between relatively wet and mild winters and hot and dry summers. Piedmonts represent typical semi-arid morphological complexes set at the interface between mountainous areas and plains or depressions. Within this context, an important adaptation effort was needed to account for the site's specificity.

First, during ***phenomena*** **map** design, geomorphic flood hazard assessment methods for **semi-arid and Mediterranean regions** were explored (e.g. the French hydro-geomorphological method, see among others Ballais et al. 2011) and certain elements adapted to the final map. Then, geomorphic hazard assessment methods adapted for the typical **alluvial fan environment** were included to mapping (e.g. NRC 1996).

The semi-arid hydro-climatic region has an important role in catchment's hydrological behaviour. Indeed, catchment sparse vegetation and thin soils as well as high rainfall intensity had to be accounted for in **hydrological modelling** as catchments behave like **quasi-impervious areas** during rain events, producing **flash floods**. This insight oriented our choice of hydrological models, especially when modelling infiltration processes and designing flood hydrographs.

The most important constraint in **hydraulic modelling** of flood development within the Beni Mellal urban area came from modelling the **alluvial fan hydraulic behaviour**. As 1-dimensional models have proven to be insufficient in terms of process representation, a 2-dimensional hydrodynamic model was used in order to account for topography complexity and for the flash flood aspect of the modelled events.

2) How to assess hazard in a qualitative and quantitative manner in a situation of poor data availability and respond to the cost-effectiveness criterion that would guarantee this method's dissemination in developing countries?

Data scarcity and / or quality represented an important methodological challenge throughout this study, from base maps to calibration needs (Reynard et al. 2013).

As no measured hydrometeorological data were available on the studied catchments, the best way to correctly assess hazard was to **combine field methods with model computations** throughout the assessment process. When modelling catchment hydrological behaviour, we focussed on known events that occurred during the survey period that we treated as reference events. In the modelling process we used all the available information and data in order to compensate the lack of classical data sources (gauging networks, radar data). For example, we used as an input free-access rainfall data (TRMM datasets) that was distributed in time and spatially covered the studied area and we undertook post-flood field campaigns in order to collect model verification data. Model verification with field data allowed extrapolating the model to the 20, 50, and 100-year rainfall events. The hydraulic model was "calibrated" in a similar way, using field-mapped flood extents for a known event, before being extrapolated to high, medium and low probability flood events.

Data scarcity also compelled us to use **parsimonious models** that would offer the best balance between available input data and the desired output precision. For example, in hydrologic modelling we summarized catchment behaviour to three essential processes that explain it sufficiently well: infiltration, direct runoff and routing. Lacking or incomplete data require in certain cases to **create** the needed set of **data**, as for example manually fulfilling gaps in the urban buildings dataset, manually designing stream geometry that existent DTM failed to represent, or deriving soil cover information from other information sources (geology, land cover).

These strategies allowed us to attain a good **cost-effectiveness** balance even if they may prove **time-consuming**. One can also fulfil this criterion by using open-source technologies (e.g. the HEC-HMS hydrological modelling platform). Yet, in certain situations, the need to obtain correct and realistic assessments, needs a **balance with cost-effectiveness**. Indeed, hydraulic modelling of flood events in the specific alluvial fan environment required the use of a commercially licensed model (TUFLOW).

3) At what degree this method is adaptable to the new context and which are the elements of difficulty for method adjustment?

This study's results suggest that the Swiss methodology for hazard assessment and mapping is highly adaptable to different contexts as the assessment process is regulated in a **flexible** way during different stages. Indeed, the *phenomena* map was thought as an **adaptable tool** capable of integrating very different sites and geomorphic situations. Actual adaptations to specific climatic or geomorphic contexts can therefore integrate the method. Likely, the **modelling steps** can be adjusted to data and needs, provided they output the required assessment items, i.e. water depth, velocity, and flood maximum extent for a given flood event. Then, the **assessment criteria** for defining danger or hazard as high, medium or low are based on generally accepted and valid thresholds. For example, water depth higher than 2m or water velocity higher than 2m/s represent a threat for people and animals lives if exposed directly to flooding.

Difficulties in adapting the Swiss method for hazard assessment and mapping are mainly **methodological** (e.g. data scarcity or lack of access) or can relate to specificities in **hazard assessment practice** in the adaptation environment. For example, the Swiss hazard matrix could not be transferred as such to the Moroccan site as in practice (and available data) low, medium and high flood probability thresholds differ between Switzerland and Morocco.

9.2.2. Institutional objective

1) In the present legal framework related to natural hazards in general and floods in particular, which could be the place of hazard maps as flood risk mitigation tools especially in the context of the new developments in risk management related to the Hyogo Framework for action?

The analysis of the present risk-related legal framework revealed that **passive measures** such as the implementation of hazard assessment to planning are **not yet addressed** in Morocco, and that regulations highlight active, structural measures of protection. Nevertheless, **in practice** and at the **regional level**, the need to rethink risk management has been crystallized in certain approaches that account for the value of hazard-aware planning. For example in the Beni Mellal region, an agreement between water managers and urban planners stipulates that the Catchment Agency provides hazard assessment to be integrated in future master plans within the Beni Mellal Urban Agency area of scope. Another regional example consists of the Al Hoceïma project of designing "development aptitude maps" based on a multi-hazard assessment (IMS-RN 2011). At the **national level**, a recent project supported by the Moroccan government, SDC and the World Bank aims at assessing risks at the nation's scale, defining sectorial strategies of coping at the ministerial level, and mainstreaming hazard-aware planning at the regional and local level (SDC 2011). This project aligns along the Hyogo goals of reducing risk by reducing vulnerability.

Regional and national projects reveal the need for integration and reconsideration of passive measures in risk management; however, Morocco will attain sustainable change only if **regulations change** in order to enforce the bond between risk management and urban planning. The new Moroccan **Urban Code** could provide a valuable legal platform for achieving this goal..

2) The role of institutional stakeholders (e.g. planners and water managers) may be crucial for effective flood risk mitigation at the regional and local level. What are their effective roles in management and how could these roles be rethought in the sense of an integrated risk management approach?

This study's inquiry in risk management in Beni Mellal provided insights on institutional stakeholders' roles and interactions in the management process and could point out several inadequacies and weaknesses as well as positive aspects. The analysis suggests that **risk management is unbalanced** in that active risk mitigation measures dwarf all other prevention intervention and reconstruction measures; within active measures, too many stakeholders share sectorial responsibilities resulting in **timing problems** and role confusion; relationships proved to be complex: on one hand, risk management follows a **top-down** logic, as the Wilaya leads the process at all stages, while on the other, hand institutional actors developed **horizontal collaboration** interactions with positive consequences in risk management.

In order to achieve risk management integration, **passive measures** such as hazard-aware planning should gain importance, actors should better **define** their **roles**, be it within the established hierarchy or in horizontal relationships, and more attention should be paid to **rehabilitation measures** in order to increase the communities' resilience to hazards. Risk management should open up to innovative solutions, be it by internal collaborations, or by accessing external knowledge pools such as universities, that could provide more integrative and multidisciplinary methodologies for hazard assessment or policy exploration.

3) What is the institutional stakeholders' approach to flood hazard mapping and maps implementation?

As stated above, passive measures are still insufficiently used or even acknowledged in regulations. Nevertheless, in practice, water managers and urban planners recognize their importance so that at the regional level, an agreement was signed in order to transfer hazard assessment results to master plans. Integration of these measures is still in process, and a better legal framework is necessary to generalize the assessment to planning bond and to clearly define procedures within an integrated risk management approach.

9.2.3. Applied objective

1) What are the best-suited knowledge transfer strategies for making this study's project acceptable and replicable in the studied context? Is academic collaboration an asset in knowhow transfer?

The knowledge transfer literature suggests that successful transfer depends, among others, on the **perceived value** of the knowledge to be transferred (Gupta & Govindarajan 2001). In this context, the interest the Moroccan authorities expressed in the Swiss methodology for hazard assessment and mapping and the resulting cooperation project proves that this methodology is perceived as an asset in risk management and is potentially applicable in Morocco.

Practical knowledge or know-how is ideally transferred by **demonstration or "show-how"** (Roberts 2000). The adaptation of the Swiss danger map methodology to the specific case of Beni Mellal represents such "show-how" strategy. Indeed, the designed maps and scientific reports were addressed to local authorities as a set of decision-making tools. However, they also represent the expression of an adaptation effort that demonstrates **how indicative danger maps can be produced** in the specific hydro-climatic and socio-economic context.

The map adaptation remains however ineffective without implementation in planning strategies. Therefore, a set of **mainstreaming strategies** is needed in order to communicate danger map concepts and their consequences for risk mitigation and thus prepare the path for implementation. Workshops, guidelines and other types of communication tools are needed in the process. For example, the SDC underwent efforts in communicating the outcomes of its involvement in DRR in Morocco, including this project, by organizing a mainstreaming conference in Fez (October 2012). Moreover, a guideline collection for designing (indicative) danger maps is projected as a direct outcome of this study.

The academic milieu represents an important pool of **multidisciplinary knowledge** that can address the various facets of risk management (legal, scientific, social) in an integrative manner. Therefore, we suggest academic collaboration in risk management is an asset for finding innovative solutions for hazard assessment, map design or implementation investigations.

2) How the adapted map and the manner hazard information is encoded within it could be perceived by end-users, managers and the public?

This study briefly explored the map perception and acceptability issue, using mostly a theoretical point of view. Literature suggests that thresholds used to classify hazard are justified by psychological risk tolerance limits related to successive stages: acknowledging risk, taking action to mitigate risk, and finally rejecting risk as intolerable (e.g. Schoeneich et al. 1998). Danger map colour coding is believed to represent well these thresholds, at least in flood hazard assessment and mapping. We therefore suggest that the indicative danger map is capable to clearly communicate the hazard message to end-users. Nevertheless, map perception should be tested before implementation.

9.3. Final discussion and perspectives

The objective of this study was to adapt the Swiss methodology for hazard assessment and mapping to a Moroccan case study, and to explore the potential implementation of hazard assessment to planning, in the sense of an integrated risk management approach. We consider these objectives as attained. Nevertheless, we are aware of a number of limitations of the present work, especially relating to its institutional objective. Indeed, the implementation of danger maps was only explored from an institutional point of view, with a focus on institutional vulnerability as an indicator for the risk management conditions. We chose this limited approach for two main reasons: first, the short survey periods in Beni Mellal did not allow for large surveys to be undertaken; second, vulnerability mapping is not observed in the Swiss methodology even though it is often desirable in developing countries (Zimmermann et al. 2005), as the means to inventory damage potential and set protection objectives are scarcer in these countries. Risk management stakeholders' perception of danger maps needs to be studied in view of implementation: we consider this to be a limit to our work, mainly related to the short time of survey that did not allow putting the map document into a perspective. Finally, this study's multidisciplinary approach demanded us to acquire specific knowledge in disciplines other than the basic geomorphology field (e.g. hydrology, hydraulics); the learning process proved relatively time-consuming.

This study achieved the pioneering effort of adapting a well-established hazard assessment and mapping methodology in a different climatic and socio-economic context. As such, the methodology can certainly be enhanced and some of the problems arisen by this research need to be deepened.

First, in this study we focussed on adapting the Swiss hazard assessment method to only one type of hazard, namely floods. Indeed, the Swiss method is applicable in a **multi-hazard assessment approach** although each hazard assessment potentially requires adaptations comparable to the ones undertaken within this study. A methodological adaptation of hazard assessment for landslides, avalanches or debris flows could thus be undertaken, and the integration of multi-hazard assessment in one cartographic document needs to be tested. Moreover, the integration to danger maps of the seismic hazard assessment, sensitive in Morocco, could open a novel research panel, as this hazard is not presently addressed by the Swiss methodology.

Then, this research did not explore in depth the **map acceptability and reproducibility** in the new context. Indeed, although the Swiss danger map codes are based on practical as well as psychosocial grounds, map design needs to be tested in the adaptation environment. Colour codes, risk and probability concepts used in assessment, and the notion of what is acceptable risk in a community or a society need to be clearly outlined before implementing such documents to development strategies. Moreover, the potential adaptation of other hazard assessments (landslides, for example) might arise new questions on colour code adequacy or hazard probability.

Finally, a series of questions arise, related to the **implementation** of hazard assessment into **land use planning**. Indeed, regulation adjustment, risk management advancement towards integration, and the practical modalities of implementing hazard assessment require setting up a series of theoretical and practical knowledge in the legal and administrative fields.

Within this study, we answered a few questions about how hazard assessment and mapping knowledge can be transferred to different natural and socio-economic environments. More than answering questions, this study opens a series of practical and research perspectives in the risk management field related to the best-suited methodologies to be adopted but also to how hazard or danger maps could be perceived, and potentially adopted by target communities. We hope that this pioneering research sets the basis for future explorations that can positively impact risk management in contexts similar to the one described in this study.

Danger maps represent effective risk mitigation tools when they are implemented to planning. Indeed, danger maps provide the basis for addressing and mitigating territorial vulnerability. Moreover, danger maps represent sound communication tools that make hazard visible to the exposed people; thus, danger maps contribute to mitigate peoples' vulnerability by providing them knowledge on risks. In this perspective, danger maps represent tools for establishing a risk culture.

References

A

ABHOER (2004). *Protection contre les inondations dans la zone d'action de l'Agence dubassin hydraulique Oum-er-Rhbia,* Agence du bassin hydraulique Oum-er-Rhbia (A.H.O.E.R.), Beni Mellal.

ADI (2004). *Etude de protection contre les inondations. Etude hydraulique et propositions d'aménagement. Province de Beni Mellal*, Compagnie d'Aménagement Agricole et Développement Industriel (A.D.I), Beni Mellal.

ADI, ABHOER (2006). *Atlas des zones inondables du bassin versant D'Oum er Rbia,* Beni Mellal, Agence du bassin hydraulique Oum-er-Rhbia (A.H.O.E.R.), Compagnie d'Aménagement Agricole et Développement Industriel (A.D.I), Beni Mellal.

Alavi M., Leidner D. E. (2001). Review: knowledge management and knowledge management systems: conceptual foundations and research issues, *MIS Quartely* 1(25), 107-136.

Alcántara-Ayala I. (2002). Geomorphology, natural hazards, vulnerability and prevention of natural disasters in developing countries, *Geomorphology* 47, 107-124.

Alcántara-Ayala I. (2004). Flowing mountains in Mexico. Incorporating local knowledge and initiatives to confront disaster and promote prevention, *Mountain Research and Development* 1(24), 10-13.

Alfieri l., Laio F., Claps P. (2008). A simulation experiment for optimal design hyetograph selection, *Hydrological Processes* 22, 813-820.

Alwang J., Siegel P. B., Jorgensen S. L. (2001). *Vulnerability: a view from different disciplines*, Social Protection discussion paper 115, The World Bank, 42p.

ARE (2013). Carte de dangers, retrieved 28.05.2013, http://www.are.admin.ch/themen/raumplanung.

ARE, OFEG, OFEFP (2005). *Aménagement du territoire et dangers naturels, recommandations*, Office fédéral du développement territorial (ARE), Office fédéral des eaux et de la géologie (OFEG) et Office fédéral de l'environnement, des forêts et du paysage (OFEFP), Berne.

Arnaud-Fassetta G., Masson E., Reynard E. (eds.) (2013). *European continental hydrosystems under changing water policy*, Verlag Dr. Friedrich Pfeil, Münich.

Aysan Y. F. (1993). Vulnerability assessment. In Merriman P. A., Browitt C. W. A. (eds.) *Natural disasters: protecting v ulnerable* communities, Thomas Telford, London.

B

Bachaoui B., Bachaoui E. M., El Harti A., Bannari A., El Ghmari A. (2007) Cartographie des zones à risque d'érosion hydrique : exemple du Haut Atlas marocain. *Revue Télédétection* 7(1-4), 393-404.

Bahat Y., Grodek T., Lekach J., Morin E. (2009). Rainfall-runoff modelling in a small hyper-arid catchment, *Journal of Hydrology* 373, 204-217.

Bahzad A. (1982). *Recherches hydrologiques et hydrochimiques sur quelques karsts méditerranéens – Liban, Syrie et Maroc*. PhD thesis, University Aix-Marseille II, Marseille.

Ballais J-L., Garry G., Masson M. (2005). Contribution de l'hydrogéomorphologie à l'évaluation du risque d'inondation: le cas du Midi méditerranéen français. *C.R Géoscience*, 337, 1120-1130.

Ballais J-L., Chave S., Dupont N., Masson E., Penven M-J. (2011). *La méthode hydrogéomorphologique de détermination des zones inondables*, Physio-Géo, collection "Ouvrages", retrieved 2.12.2010, www.physio-geo.fr.

Baloutsos G., Bourletsikas A., Baltas E. (2010). Interception, throughfall and stemflow of maquis vegetation in Greece, *WSEAS Transactions on Environment and Development* 1, 21-32.

Balzano A. (1998). Evaluation of methods for numerical simulation of wetting and drying in shallow water flow models, *Coastal Engineering* 34, 83-107.

Bandaragoda C., Greenberg J., Dumas M., Gill P. (2012). Lower Nooksack Water Budget Overview. *In Whatcom County*, WA: WRIA 1 Joint Board. Retrieved 23.01.2013, http://wria1project.whatcomcounty.org/.

Barton C. L. (2001). *Flow through an abrupt constriction – 2D hydrodynamic model performance and influence of spatial resolution.* Thesis submitted as partial fulfilment for Master of Engineering Science, Environmental Engineering, Griffith University.

Bates P. D., De Roo A. P. J. (2000). A simple raster-based model for flood inundation simulation, *Journal of Hydrology* 236, 54-77.

Bedient P. B., Huber W. C. (2002). *Hydrology and Floodplain Analysis*, 3rd Edition, Prentice Hall, Upper Saddle River, New Jersey.

Benjelloun Y. (2009). *Estimation du risque d'inondation utilisant les moyens de la télédétection et systèmes d'information géographique. Cas de l'inondation de Mohammedia*. Projet de fin d'études, Ecole Mohammedia d'Ingénieurs (EMI) Rabat.

Berz G., Kron W., Loster T., Rauch E., Schimetschek J., Schmieder J., Siebert A., Smolka A., Wirtz A. (2001). World map of natural hazards – a global view of the distribution and intensity of significant exposures, *Natural Hazards* 23, 443–465.

Beven K, Binley A. (1992). The future of distributed models: model calibration and uncertainty prediction, *Hydrological Processes* 6, 279-298.

Birkmann J. (2006). Measuring vulnerability to promote disaster resilient societies. Conceptual frameworks and definitions. In Birkmann J. (ed.) *Measuring vulnerability to natural hazards. Towards disaster resilient societies.* United Nations University Press, Tokyo.

Blaikie P., Cannon T., Davis I., Wisner B. (1994). At risk: natural hazards, people's vulnerability, and disasters, Routledge, London.

Blair T. C., McPherson G. J. (1994). Alluvial fan processes and forms. In Abrahams A.D., Parsons A. J. (eds.) *Geomorphology of desert environments,* Chapman & Hall, London, 413-467.

Blöschl G., Viglione A. (2009). On the role of storm duration in the mapping of rainfall to flood return periods, *Hydrology and Earth System Sciences* 13, 205-216.

Boer M., Puigfäbregas J. (2005). Effects of spatially structured vegetation patterns on hillslope erosion in a semi-arid Mediterranean environment, *Earth processes and forms* 2(30) 149-167.

Bollin C., Cardenas C., Hahn H., Vatsa K. S. (2003) Natural Disaster Network; Disaster Risk Management by Communities and Local Governments, Washington, D.C.: Inter-American Development Bank, retrievevd 12.03.2011. http://www.iadb.org/sds.

Borga M., Anagnostou E. N., Blöschl G., Creutin J-D. (2010) Flash floods: Observations and analysis of hydro-meteorological controls, *Journal of Hydrology*, 394(1), 1-3.

Bouchaou L. (1997). Contribution à la connaissance de l'aquifère karstique de l'Atlas de Beni Mellal (Maroc), *Karst hydrology (Proceedings of workshop W2 held in Rabat, Morroco, April-May 1997),* IAHS publications 247, 117-126.

Brevnova E. V. (2001). *Green-Ampt Infiltration Model Parameter Determination Using SCS Curve Number (CN) and Soil Texture Class, and Application to the SCS Runoff Model*, Morgantown, West Virginia.

BRL, A.D.I., Aquater (2004). *Etude du Plan National de protection contre les inondations et impacts des ouvrages de protection sur l'environnement. Rapport de synthèse,* Casablanca.

Bull W. D. (1977). The alluvial fan environment, *Progress in physical geography* 1, 222-270.

Burton I., Kates R.W. (1964). The perception of natural hazards in resource management, *Natural Resources Journal* 3(3), 412-441.

Burton I., Kates R., White G. (1978). *The environment as hazard*, Oxford University Press, New York.

C

Camarasa Belmonte A. M. (1993). La estructura interna de las tormentas mediterráneas. *Cuaderno de geografia* 54, 169-188.

Camarasa-Belmonte A. M., Soriano-García J. (2008). Peligro, vulnerabilidad y riesgo de inudaciòn en ramblas mediterraneas : los llanos de Caraixet y Poyo, *Cuadernos de Geografia* 83, 1-26.

Camarasa-Belmonte A. M., Soriano-García J. (2012). Flood risk assessment and mapping in peri-urban Mediterranean environments using hydrogeomorphology. Application to ephemeral streams in the Valencia region (eastern Spain), *Landscape and Urban Planning* 2(104), 189-200.

CAPRA (2012). *CAPRA Initiative: Integrating disaster risk information into development policies and programs in Latin America and the Caribbean,* Central American

Probabilistic Risk Assessment, retrieved 6.05.2013 http://www.ecapra.org/sites/default/files/documents/CAPRA_Submission.pdf.

Cardona O. D. (2003). The need of rethinking the concepts of vulnerability and risk from a holistic perspective: necessary review and criticism for effective risk management. In Bankoff G., Frerks G., Hilhorst D. (eds.) *Mapping vulnerability, disasters, development and people*, Earthscan Publishers, London.

Carlyle-Moses D. E. (2004). Throughfall, stemflow and canopy interception loss fluxes in a semi-arid Sierra Madre Oriental Matorral community, *Journal of Arid Environments*, 58, 181–202.

Chalabi M. (2010). *Rapport national de suivi sur la mise en oeuvre du Cadre d'action de Hyogo (2009-2011), intermédiaire*. Retrieved 20.03.2013, http://www.preventionweb.net.

Charteris A. B., Syme W. J. (2001). *Urban Flood Modelling and Mapping – 2D or not 2D,* Conference on Hydraulics in Civil Engineering, Hobart, November 2001, retrieved 04.11.2012, www.tuflow.com/download/publications.

Chave S., Ballais J-L. (2006). From hydrogeomorphology to hydraulics computations: a multidisciplinary approach of the flood hazard diagnosis in the Mediterranean zone, *Zeitschrift für Geomorphologie*, 4 (50), 523-540.

Chave S. (2002). Pertinence de la cartographie hydrogéomorphologique dans l'approche des inondations rares à exceptionnelles: exemples de sept bassins fluviaux dans les Corbières et le Minervois, *Géomorphologie: relief, processus, environnement* 4, 297-306.

Chow V. T. (1959). *Open channel hydraulics*, McGraw – Hill, New York.

Chow V. T., Maidment D. R., Mays L. V. (1988). *Applied hydrology*, McGraw-Hill, New York.

Cohen J. (1960). A coefficient of agreement for nominal scales, *Educational Psychology Measurement* 1(20), 37-46.

Cohen W. M., Levinthal D. A. (1990). Absorptive capacity: a new perspective on learning and innovation, *Administrative Science Quarterly* 35, 128-152.

Coque R. (2002). *Géomorphologie*, Armand Colin, Paris.

Congalton R. G. (1991). A review of assessing the accuracy of classifications of remotely sensed data, *Remote Sensing of the Environment* 37, 35-46.

Cordery I., Pilgrim D. H, Rowbottom I. A. (1984). Time patterns of rainfall for estimating design floods on a frequency basis, *Water science and technology* 16(8-9), 155-165.

Covello, V. T., Mumpower, J. (1985), Risk analysis and risk management: an historical perspective, *Risk Analysis* 5, 103–120.

D – E

Dauphiné A. (2001). *Risques et catastrophes*. *Observer, spatialiser, comprendre, gérer*. Armand Colin, Paris.

Davies S. (1996). *Adaptable livelihoods. Coping with food insecurity in the Malian Sahel*, St. Martin's Press, New York.

D'Ercole R. (1994). Les vulnérabilités des sociétés et des espaces urbanisés: concepts, typologie, modes d'analyse. *Rev. Géogr. alpine* 82(4), 87-96.

De Jong S. M., Jetten V. G. (2007). Estimating spatial patterns of rainfall interception from remotely sensed vegetation indices and spectral mixture analysis, *International Journal of Geographical Information Science*, 5(21), 529-545.

De Moël H., Van Alphen J., Aerts J. C. J. H. (2009). Flood maps in Europe – methods, availability and use. *Natural Hazards and Earth System Sciences* 9, 289-301.

De Vera M. R. (1984). Rainfall-runoff relationship of some catchments with karstic geomorphology under arid and semi-arid conditions, Journal of hydrology 68(1-4), 85-93.

DIREN-PACA (2007). *L'approche hydrogéomorphologique en milieux méditerranéens. Une méthode de détermination des zones inondables.* Document d'information, Direction Régionale de l'Environnement Provence – Alpes – Côte d'Azur, retrieved 13.10.2009, http://www.paca.developpement-durable.gouv.fr.

El Hames A. S. (2012). An empirical method for peak discharge prediction in ungauged arid and semi-arid region catchments based on morphological parameters and SCS curve number, *Journal of Hydrology* 456, 94-100.

El Khalki Y., Hafid A. (2002). Turbidité, indicateur du fonctionnement perturbé du géosystème karstique de Beni Mellal, *Karstologia* 40, 39-44.

El Khalki Y., Benyoucef A. (2005). Crues et inondations de l'oued El Handak: genèse, impact et propositions d'aménagement (Atlas de Beni Mellal). *Etudes de Géographie physique* 32, 47-61.

El Khalki Y., Taïbi A.N., Benyoucef A., El Hannani M., Hafid A., Mayoussi M., Zmou A., Ragala R., Geroyannis H. (2005) Processus d'urbanisation et accroissement des risques à Beni Mellal (Tadla-Azilal, Maroc): apports des SIG et de la télédétection, *Mosella* 30(1-4), 148-161.

Eschenbach T. G. (1992). Spiderplots versus tornado diagrams for sensitivity analysis, *Interfaces* 6(22), 40-46.

EU (2007). *Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks*, European Union, Brussels.

F – G

FAO (2001). *SOTER Maroc, une base de données digitale sur les sols et le relief du Maroc,* Atelier sur les bases de données SOTER dans les pays de l'Union du Maghreb arabe, organisé conjointement par FAO Afrique du Nord, Direction des aménagements fonciers, Institut d'Agronomie et vétérinaire Hassan II, Ecole nationale d'agriculture de Meknes, Rabat 12-16 novembre 2001.

FEMA (2000). *Guidelines for determining flood hazards on alluvial fans*. Federal Emergency Management Agency, Retrieved 20.3.2011 http://fema.gov.

FEMA, BESR, NRC (2009). *Mapping the zone: Improving flood map accuracy,* Committee on FEMA Flood Maps (FEMA); Board on Earth Sciences and Resources (BESR) / Mapping Science Committee; National Research Council (NRC), National Academies Press, Washington D.C.

Fernandez-Lavado C., Furdada G., Marqués M. A. (2007). Geomorphological method in the elaboration of hazard maps for flash-floods in the municipality of Jucuaran (El Salvador), *Natural Hazards and Earth System Sciences* 7, 455-465.

Frank E., Sofia G., Fattorelli S. (2012). Effects of topographic data resolution and spatial model resolution on hydrodynamic and hydro-morphological models for flood risk assessment. In Mambretti S. (ed.) *Flood risk assessment and management*, WIT Press, Southampton, 23-34.

French R. H. (1985). *Open-channel hydraulics*, McGraw-Hill, New York

Fuchs S., Spachinger K., Dorner W., Rochman J., Serrhini K. (2009). Evaluating cartographic design in flood risk mapping, *Environmental Hazards* 8, 52-70.

Furdada G., Calderon E. L., Marqués M. A. (2008). Flood hazard map in La Trinidad (Nicaragua). Method and results, *Natural Hazards* 45(2), 183-195.

Gall M., Boruff B. J., Cutter S. L. (2007). Assessing flood hazard zones in the absence of digital flood plain maps: comparison of alternative approaches, *Natural Hazards Review* 8(1), 1-12.

Garry G., Graszk E., Hubert T., Guyot P., Roy J-L. (1999). *Plans de prevention des risques. Guide méthodologique*, La documentation Française, Paris.

Gaume E., Borga M. (2008). Post-flood field investigations in upland catchments after major flash-floods: proposal of a methodology and illustrations. *Journal of flood risk management* 1, 175-189.

GFDRR (2012)a. *GFDRR programs: disaster risk reduction building resilience in changing climate*, The World Bank global facility for disaster reduction and recovery, 20.05.2013 https://www.gfdrr.org, 16p.

GFDRR (2012)b. *Disaster Risk Management in Central America: GFDRR Country Notes,* The World Bank global facility for disaster reduction and recovery, retrieved 20.05.2013 https://www.gfdrr.org, 89 p.

Ghavidelfar S., Alvankar S. R., Razmkhah A. (2011). Comparison of the lumped and quasi-distributed Clark runoff models in simulating flood hydrographs on a semi-arid watershed, *Water Resources Management* 25, 1775-1790.

Giorgi F., Lionello P. (2008). Climate change projections for the Mediterranean region, *Global and planetary change* 63, 90-104.

Gupta A., Govindarajan V. (2000). Knowledge flows within multinational corporations, *Strategic Management Journal* 21, 473-496.

Gumbel E. J. 1954. Statistical theory of extreme values and some practical applications, *Applied Mathematics Series*, 33.

Guzetti F., Carrara A., Cardinalii M., Reichenbach T. (1999). : an aid to a sustainable development, *Geomorphology* 31, 181-216.

H

Hardy R. J., Bates P. D., Anderson M. G. (1999). The importance of spatial resolution in hydraulic models for floodplain environments, *Journal of Hydrology* 216, 124-136.

Hernandez M., Miller S. N., Goodrich D. C., Goff B. F., Kepner W. C., Edmonds C. M., Jones K. B. (2000). Modeling runoff response to land cover and rainfall spatial variability in semi-arid watersheds**,** *Environmental Monitoring and Assessment* 64, 285-298.

Hewitt K. (2013). Environmental disasters in social context: toward a preventive and precautionary approach, *Natural Hazards* 66, 3-14.

Hiroki K. (2003). *Flood hazard mapping in Japan*. International training program on total disaster risk reduction, 10-13 June 2003, retrieved 20.06.2012, http://www.adrc.asia/publications/TDRM2003June/12.pdf

Hirt C. W. (2013). Implicit vs. explicit methods, *CFD 101: The basics of computational fluid dynamics modelling*. Retrieved 16.03.2013, www.flow3d.com/cfd101.

Hjelmfelt A. T. (1980). Curve number procedure as infiltration method, *Journal of the Hydraulics Division* 6(106), 1107-1110.

Hong Y., Adler R. F., Negri A., Huffman G. J. (2007). Flood and Landslide Applications of Near Real-time Satellite Rainfall Estimation, *Journal of Natural Hazards* 43, 285-294.

Hooke J. M. (2006). Human impacts on fluvial systems in the Mediterranean region, *Geomorphology* 79, 311-335.

Hornberger G. M., Spear R. C. (1981). An approach to the preliminary analysis of environmental systems, *Journal of Environmental Management* 12, 7-18.

Huffman G. J., Adler R. F., Bolvin D. T., Nelkin E. J. (2009). The TRMM multi-satellite precipitation analysis (TMPA). In: Hossain F., Gebremichael M. (eds.) *Satellite applications for surface hydrology*, Springer, 1-23.

Hugonie G. (2004) Les espaces des risques dans le domaine méditerranéen, In Wackermann G. *La géographie des risques dans le monde*, Ellipses, Paris.

Hunter N. M., Bates P. D., Neelz S., Pender G., Villanueva I., Wright N. G., Liang D., Falconer R. A., Lin B., Waller S., Crossley A. J. (2008). Benchmarking 2D hydraulic models for urban flooding, *Water Management* 161, 13-30.

Huxley C. D. (2004). *TUFLOW Testing and Validation* Undergraduate Thesis for Bachelor of Engineering in Environmental Engineering, School of Environmental Engineering, Griffith University.

I – K

IMS-RN (2011). *Risque inondation et crues torrentielles dans la région d'Al Hoceima (Maroc). Complément 5. Modélisation hydrologique et hydraulique* *complémentaires pour des périodes de retour Q10, Q25 et Q50 pour les secteurs du Riss (inondation de plaine) et de Bousekkour (crue torrentielle) et comparaison avec le Q100*, Ingénieurie des mouvements du sol et des risques naturels, Septembre 2011, Casablanca, 11p.

IPCC (2007). *Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the Intergovernmental Panel on Climate Change*, Parry M. L., Canziani O. F., Palutikof J. P., Van der Linden P. J., Hanson C. E (eds.), Cambridge University Press, Cambridge.

IPCC (2012). *Managing the risks of extreme events and disasters to advance climate change adaptation. a special report of working groups I and II of the Intergovernmental Panel on Climate Change*, Field, C. B., Barros V., Stocker T. F., Qin D., Dokken D. J., Ebi K. L., Mastrandrea M-D., Mach K. J,. Plattner G. K., Allen S. K., Tignor M., Midgley P. M. (eds.). Cambridge University Press, Cambridge.

Jenny H. (1941). *Factors of soil formation, a system of quantitative pedology,* McGraw-Hill, New York.

Kaddaf A., Boufous A. (2010). *Etude de protection contre les inondations du nouveau port de Nador.* Projet de fin d'études, Ecole Mohammedia d'Ingénieurs (EMI) Rabat.

Kienholz H., Krummenacher B. (1995). *Dangers naturels, Recommandations. Légende modulable pour la cartographie des phénomènes*. Berne, Office fédéral de l'économie des eaux (OFEE), Office fédéral de l'environnement, des forêts et du paysage (OFEFP).

Kienholz H. (2005). Analyse und Bewertung alpiner Naturgefahren. Eine Daueraufgabe im Rahmen des integralen Risikomanagements, *Geographica Helvetica* 60 1), 3-15.

Kimble, C. (2013). Knowledge management, codification and tacit knowledge *Information Research*, 18(2) paper 577. Retrieved 3.06.2013, http://InformationR.net/ir/18-4/paper577.html.

Kuhlicke C. (2013). Resilience: a capacity and a myth: findings from an in-depth case study in disaster management research, *Natural Hazards* 67, 61-76.

Kunz M., Hurni L. (2008): Hazard maps in Switzerland. State-of-the-art and potential improvements. *Proceedings of the 6th ICA Mountain Cartography Workshop, Lenk (Switzerland)*, 133-138.

L

Lane S. N. (1998). Hydraulic modelling in hydrology and geomorphology: a review of high resolution approaches, *Hydrological Processes* 12, 1131-1150.

Lane S. N. (2005). Roughness – time for a re-evaluation? *Earth Surface Processes and Landforms* 30, 251-253.

LAS (2010). *The Arab Strategy for Disaster Risk Reduction 2020, Final version adopted by the Council of Arab Ministers Responsible for the Environment, resolution # 345, in its 22nd session held at the League of Arab States 19-20 December 2010,* retrieved 15.05.2013, http://www.preventionweb.net (20p)

Lasri M., Obda K., Taous A., Amyay M., Reynard E. (2011). L'agglomération de Fès et sa périphérie face au risque d'inondation. Résultats préliminaires. *Proceedings of the conference "Aménagement périurbain: processus, enjeux, risques et perspectives", 17-18 février 2010*, 189-206.

Lasri M. (2013). *L'agglomération de Fès face aux risques d'inondation. De l'étude hydrologique à la carte de danger*, PhD thesis, Université Sidi Mohamed ben Abdellah, Fez (in press).

Lateltin O. (1997). *Prise en compte des dangers dus aux mouvements de terrain dans le cadre des activités de l'aménagement du territoire, Recommandations*, Office fédéral de l'économie des eaux (OFEE), Office fédéral de l'aménagement du territoire (OFAT), Office fédéral de l'environnement, des forêts et du paysage (OFEFP), Berne.

Latron J., Llorens P., Gallart F. (2009). The hydrology of Mediterranean mountain areas. *Geography Compass*, 3(6), 2045-2064.

Lavell A. (ed.) (1994). *Viviendo en riesgo. Comunidades vulnerables y prevención de desastres en America Latina*, LA RED, Bogotà.

Lionello P., Abrantes F., Congedi L., Dulac F., Gacic M., Gomis D., Goodess C., Holger H., Kutiel H., Lutherbacher J., Plantpon S., Reale M., Schröder K., Struglia M. V., Toreti A., Tsimplis M., Ulbrich U., Xoplaki E. (2012). Mediterranean climate: background information. In Lionello P. (ed.) *The climate of the Mediterranean region*, Elsevier, Amsterdam.

Liu G., Craig J. R., Soulis E. D. (2011). Applicability of the Green-Ampt infiltration model with shallow boundary conditions, *Hydrologic Engineering* 16 (3), 266-273.

Loat R., Petrascheck A. (1997). *Prise en compte des dangers dus aux crues dans le cadre des activités de l'aménagement du territoire,* Recommandations, Office fédéral de l'économie des eaux (OFEE), Office fédéral de l'aménagement du territoire (OFAT), Office fédéral de l'environnement, des forêts et du paysage (OFEFP), Berne.

Loat R., Zimmermann M. (2004). La gestion des risques en Suisse. In: Veyret, Y., Garry G., Meshinet de Richemenod N. (eds.) *Risques naturels et aménagement en Europe*, Armand Colin, Paris, 108-120.

Lorenz D. F. (2013). The diversity of resilience: contributions from a social science perspective, *Natural Hazards* 67, 7-24.

Loup J. (1960). *L'Oum-er-Rebia: Contribution à l'étude hydrologique d'un fleuve marocain*, Trav. Inst, Sc. Cherif 9, Rabat.

Luterbacher J., Garcia-Herrera R., Akcer-On S., Allan R., Alvarez-Castro M. C., Benito G., Booth J., Büntgen U., Cagatay N., Colombaroli D., Davis B., Esper J., Felis T., Fleitmann D., Frank D., Gallego D., Garcia-Bustamante E., Glaser R., Gonzalez-Rouco F. J., Goosse H., Kiefer T., Macklin M. G., Manning S. W., Montagna P., Newman L., Power M. J., Rath V., Ribera P., Riemann D., Roberts N., Sicre M-A., Silenzi S., Tinner W., Chronis Tzedakis P., Valero-Garcés B., Van der Schrier G., Boris Vannière B., Vogt S., Wanner H., Werner J. P., Willett G., Williams M. H., Xoplaki E., Zerefos C.S., Zorita E. (2012) A review of 2000 years of paleoclimatic evidence in the Mediterranean, In Lionello P. (ed.) *The climate of the Mediterranean region*, Elsevier, Amsterdam.

Lüthi R. (2004). Cadre juridique des cartes de danger, Série PLANAT 5, Office fédéral des eaux et de la géologie, Bienne.

M

Magnan A., Garnaud B., Billé R., Gemenne F., Hallegatte S. (2009). *The Future of the Mediterranean: from impacts of climate change to adaptation issues,* IDDRI report, 43p.

Mahbub I., Monzur A. I. (2009). Improved continuing losses estimation using initial loss-continuing loss model for medium sized rural catchments, *American Journal of Engineering and Applied Sciences* 2(4), 796-803.

Maskrey A. (1994). Comunidad y desastres en América Latina : estrategias de intervención. In Lavell A. (ed.) *Viviendo en riesgo. Comunidades vulnerables y prevención de desastres en América Latina*, LA RED, Bogotá.

Masson M., Garry G., Ballais J. L. (1996). *Cartographie des zones inondables. Approche hydrogéomorphologique*. Éditions Villes et Territoires, Paris.

Mastin M. C. (2002). *Flood-hazard mapping in Honduras in response to Hurricane Mitch*, *Water-Resources Investigations Report 01-4277,* U.S. Geological Survey (USGS), Tacoma, Washington, 38 p.

MATUHE (2001a). *Réglement de construction parasismique (R.P.S 2002) (applicable aux bâtiments)*, Royaume du Maroc, Ministère de l'Aménagement du Territoire, de l'Urbanisme, de l'Habitat et de l'Environnement, Secrétariat d'Etat à l'Habitat, Rabat.

MATUHE (2001b). First national communication. United Nations framework convention on climate change, Royaume du Maroc, Ministère de l'Aménagement du Territoire, de l'Urbanisme, de l'Habitat et de l'Environnement, Rabat.

McBratney A. B., Mendonça Santos M. L., Mynasny B. (2003). On digital soil mapping, *Geoderma* 117, 3-52.

McCuen R. H. (2003). *Modeling hydrologic change. Statistical methods*, CRC Press, New York.

McIntyre N., Al-Qurashi A. (2009). Performance of ten rainfall-runoff models applied to an arid catchment in Oman, *Environmental Modelling and Software* 24, 726-738.

McKenzie N. J., Ryan P. J. (1999). Spatial prediction of soil properties using environmental correlation, *Geoderma* 89, 67-94.

MELP – Italy (2006): *Flood Risk Management in Italy: Tools for the hydrogeological land planning*, Ministry of the Environmental Land Protection, Retrieved 29.07.2012, http://www.planat.ch/fileadmin/PLANAT/planat_pdf/alle/R0780e.pdf, 4p.

Menoni S., Molinari D., Parker D., Ballio F., Tapsell S. (2012). Assessing multifaceted vulnerability and resilience in order to design risk-mitigation strategies, *Natural Hazards* 64, 2057-2082.

Messerli B., Grosjean M., Hofer T., Núñez L., Pfister C. (2000). From nature-dominated to human-dominated environmental changes. *Quaternary Science Reviews* 19, 459-479.

Mishra S. (2009). Uncertainty and sensitivity analysis techniques for hydrologic modeling, *Journal of Hydroinformatics* 11(3-4), 282-296.

Mohanty S., Panda B., Karelia H., Issar R. (2004). *Knowledge management in disaster risk reduction: the Indian approach, an initiative under the GOI-UNDP Disaster Risk Management Programme*, Government of India retrieved 3.06.2013, http://preventionweb.net/go/2155, 8p.

Monbaron M. (1981). Sédimentation, tectonique synsédimentaire et magmatisme basique: l'évolution paléogéographique et structurale de l'Atlas de Beni Mellal (Maroc) au cours du Mésozoïque: ses incidences sur la tectonique tertiaire, *Ecologae geol. Helv*. 3(74), 625–638.

Monbaron M. (1982). Précisions sur la chronologie de la tectogenèse atlasique: exemple du domaine atlasique mésogéen du Maroc, *C.R. Acad.Sci. (Paris)* 2(294), 883–886.

Morris M. D. (1991). Factorial sampling plans for preliminary computational experiments, *Technometric*s 2, 161-174.

Munich RE (2010). *Factsheet: Natural catastrophes in differently developed economies*, Münchener Rückversicherungs-Gesellschaft, Geo Risks Research, NatCatSERVICE retrieved 3.04.2013, https://www.munichre.com/touch.

Musy A., Higy C. (1998). *Hydrologie appliquée, Cours polycopié*, Ecole polytechnique fédérale de Lausanne, Lausanne.

Musy A., Higy C. (2004). *Hydrologie. Une science de la nature*, Presses techniques et universitaires romandes, Lausanne.

N

Najine A., Jaffal M., Aïfa T., Filahi M., Arioua A., Boukdir A., Andrieux P., Rejiba F. (2006). Reconnaissance de cavités souterraines par tomographie électrique et radar géologique dans le centre ville de Béni-Mellal (Maroc), *Bulletin des laboratoires des ponts et chaussées* 260, 83-89.

Nash J. E., Sutcliffe J. V. (1970), River flow forecasting through conceptual models part I - A discussion of principles, *Journal of Hydrology* 10 (3), 282–290.

Nikolopoulos E. I., Anagnostou E. N., Hossain F., Gebremichael M., Borga M. (2010). Understanding the scale relationships of uncertainty propagation of satellite rainfall through a distributed hydrologic model, *Journal of Hydrometeorology* 2, 520-532.

Nikolopoulos E. I., Anagnostou E. N., Borga M. (2013). Using High-Resolution Satellite Rainfall Products to Simulate a Major Flash Flood Event in Northern Italy. *Journal of Hydrometeorology* 14, 171-185.

Nonaka I., Takeuchi H (1995). *The knowledge-creating company. How Japanese companies create the dynamics of innovation*, Oxford University Press, New York

Nonaka I., Toyama R., Hirata T., Bigelow S. G., Hirose A., Kohlbacher F. (2008). *Managing flow: a process theory of the knowledge-based firm*, Palgrave – Macmillan, New York.

Nonaka I., Von Krogh G. (2009). Perspective - tacit knowledge and knowledge conversion: controversy and advancement in organizational knowledge creation theory, *Organization Science*, 20(3), 635-652.

Nott J. (2006). *Extreme events. A physical reconstruction and risk assessment*, Cambridge University Press, Cambridge.

NRC (1996). *Alluvial Fan Flooding*, National Research Council, Committee on Alluvial Fan Flooding, National Academy Press, Washington DC.

NRCS (1999). *Soil taxonomy, a basic system of soil classification for making and interpreting soil surveys*, Second Edition, National Resources Conservation Service Washington D.C. Retrieved 1.3.2010, http://soils.usda.gov.

NRCS (2007). *Part 630 Hydrology. National engineering handbook,* National Resources Conservation Service, Washigton DC.

O – P

O'Brien J. S., Julien P. Y., Fullerton W. T. (1993). Two-dimensional water flood and mudflow simulation, *Journal of Hydraulic Engineering* 119(2), 244-261.

Oerlemans R. R. R., Vink P. P. (2010). *Rainfall interception experiments and interception mapping using remote sensing*, Master thesis, Faculty of Geosciences, Department of Physical Geography, Utrecht University. Retrieved 23.01.2013, http://igitur-archive.library.uu.nl.

OFEG (2001). *Protection contre les crues des cours d'eau, Directives de l'OFEG*, Office Fédéral des Eaux et de la Géologie, Berne.

OFEV (2011). *Vivre avec les dangers naturels,* Office Fédéral de l'Environnement OFEV, Berne, 8p.

OFF (1984). *Directives pour la prise en compte du danger d'avalanches lors de l'exercice d'activités touchant à l'organisation du territoire*, Office federal des forêts, Institut fédéral pour l'étude de la neige et des avalanches, Berne.

OFPP (2003*). KATARISK: Catastrophes et situations d'urgence en Suisse. Une appreciation des risques du point de vue de la protection de la population*, Office federal de la protection de la population, Berne.

Olson R. M., Wright S. J. (1998) *Essentials of engineering fluid mechanics*, Harper Row, New York.

Osterkampl W. R., Friedman J. M. (2000). The disparity between extreme rainfall events and rare floods -with emphasis on the semi-arid American West**,** *Hydrological Processes* 14**,** 2817-2829.

Oxford dictionary of physics (2009). Oxford University Press, Oxford.

Pelletier J. D., Pearthree P. A., House P. K., Demsey K. A., Klawon J. E., Vincent K. R. (2005). An integrated approach to flood hazard assessment on alluvial fans using numerical modelling, field mapping, and remote sensing. *Geological Society of America Bulletin,* 117 (9-10), 1167-1180.

Penelas M., Delaloye R., November V., Reynard E., Ruegg J. (2008). *Cartes de dangers et aménagement du territoire*, Thematic report, Action COST C19 « Impact des inondations en Suisse : processus d'apprentissage, gestion du risque et aménagement du territoire », Université de Lausanne, Université de Fribourg, Université de Zürich, Ecole polytechnique fédérale de Lausanne, Lausanne.

Pentland B. T. (1995). Information systems and organizational learning : the social epistemology of organizational knowledge systems, *Accounting, Management and Information Technologies* 5(1), 1-21.

Pilgrim D. H., Chapman T. G., Doran D. G. (1988). Problems of rainfall-runoff modelling in arid and semiarid regions, *Hydrological Sciences Journal*, 33(4), 379-400.

PLANAT (2011). *Eléments pour une nouvelle culture du risque. Rapport d'activité 2008-2011*, Plateforme nationale Dangers Naturels PLANAT, Bienne.

Polanyi M. (1967). *The tacit dimension*, Routledge and Keoan Paul, London.

Poretti (2011). *Integrated strategy for disaster risk management - Morocco*, SDC Berne, retrieved 17.05 2013, http://www.sdc-drr.net, 2p.

R

Rallison R. E., Miller N. (1981). Past, present and future SCS Runoff Procedure. *Proceedings of the International Symposium on Rainfall-Runoff Modeling*, Mississippi State University, 353-363.

Rawls W. J., Brakensiek D. L. (1982). Estimating of soil water retention from soil properties, *Journal of Irrigation and Drainage*, 166-171.

Renn O. (1992)a. Concepts of risk: a classification, in Krimsky S., Golding D. (eds.) *Social theories of risk*, Praeger, Westport.

Renn O. (1992)b. The social arena concept of risk debates, in Krimsky S., Golding D. (eds.) *Social theories of risk*, Praeger, Westport.

Reynard E., Mauch C., Thorens A. (2000). *Développement historique des régimes institutionnels de la ressource en eau entre 1870 et 2000*, Working paper de l'IDHEAP 6, IDHEAP, Chavannes-près-Renens.

Reynard E., November V. (2008). Social processes in natural disaster management. The case of recent floods in Switzerland, in Rostun J. (ed.). *COST Action C19 – Proactive crisis management of urban infrastructure*, SINTEF, Byggforsk.

Reynard E., November V., Thomi L., Penelas M., Ruegg J., Delaloye R., Zaugg-Stern M. (2008). Synthetic report, Action COST C19 « Impact des inondations en Suisse : processus d'apprentissage, gestion du risque et aménagement du territoire », Université de Lausanne, Université de Fribourg, Université de Zürich, Ecole polytechnique fédérale de Lausanne, Lausanne.

Reynard E., Werren G., Lasri M., Obda K. (2011)a. Problèmes méthodologiques liés à la cartographie des phénomènes d'inondation dans deux bassins versants marocains. *Actes de la 2e Rencontre Journée des dangers naturels (JRDN), Lausanne, 18 février 2011*, 217-222.

Reynard E., Lasri M., Werren G., Obda K., Amyay M., Taous A. (2011)b. *Carte des phénomènes d'inondation des bassins versants de Fès et Beni Mellal, Rapport rédigé dans le cadre du projet "Gestion du risqué d'inondation dans deux bassins versants marocains: Fès et Beni Mellal", financé par la Direction du développement et de la cooperation Suisse*, Lausanne, Fez, Mars 2011.

Reynard E., Lasri M., Werren G., Obda K., Amyay M., Taous A., Balin D., Lane S. N. (2012) *Etude des dangers d'inondation dans les bassins de Fès et Beni Mellal. Analyse hydrologique, carte indicative des dangers, étude de la vulnérabilité et recommandations,* Rapport rédigé dans le cadre du projet "Gestion du risque d'inondation dans deux bassins versants marocains: Fès et Beni Mellal", financé par la Direction du développement et de la cooperation Suisse, Lausanne, Fès, Novembre 2012.

Reynard E., Werren G., Lasri M., Obda K., El Khalki Y. (2013). Cartes des phénomènes d'inondation dans deux bassins versants marocains : problèmes méthodologiques, *Mémoires de la Société vaudoise de sciences naturelles* 25, 61-71.

Roberts J. (2000). From know-how to show-how ? Questioning the role of information and communication technologies in knowledge transfer, *Technology Analysis & Strategic Management* 12 (4), 429-443.

Robins C. R., Buck J. B., Wiliams A. G., Morton J. L., House P. K., Howell P. S., Yonovitz M. L. (2009). Comparison of flood hazard assessments on desert piedmonts and playas : A case study in Ivanpah Valley, Nevada, *Geomorphology* 103, 520-532.

Rossiter D. G. (2004) Technical note: statistical methods for accuracy assessment of classified thematic maps, Copyright 2004 D.G Rossiter, retrieved 15.1.2013, www.itc.nl/rossiter/teach.

S

Saïdi M., Daoudi L., Aresmouk M.H., Fniguire F., Boukrim S. (2010). The Ourika floods (High Atlas, Morocco). Extreme events in semi-arid mountain context. *Comunicações Geológicas* 97, 113-128.

Saltelli A., Tarantola A., Campolongo F., Ratto M. (2004). *Sensitivity analysis in practice - a guide to assessing scientific models*, Wiley, Chichester.

Santangelo N., Santo A., Di Crescenzo G., Foscari G., Liuzza V., Sciarotta S., Scorpio V. (2011). Flood susceptibility assessment in a highly urbanized alluvial fan: the case study of Sala Consilina (Southern Italy), *Natural Hazards and Earth System Science* 11, 2765-2780.

Schick A. P., Grodek T., Wolman M. G. (1999) Hydrologic processes and geomorphic constraints on urbanization of alluvial fan slopes. *Geomorphology* 31, 325-335

Schoeneich P., Busset-Henchoz M-C., Bridel L., Dulex-Putallaz S., Herold-Revaz A., Ledergerber R. (1997). La représentation des risques par les habitants: perception différenciée et adaptations psychologiques, *Eclogae geologie Helvetiae* 90, 463-469.

Schoeneich P., Busset-Henchoz M-C (1998). La dissonance cognitive - facteur explicatif de l'accoutumance au risque, *Revue de Géographie Alpine* 86(2), 53-62.

SDC (2008). *SDC guidelines on disaster risk reduction, 2nd edition*, Swiss Agency for Development and Cooperation, Berne, 23p.

SDC (2011). *Fact sheet RRD: Integrated Strategy for Disaster Risk Management 2011*. Retrieved 2.03 .2013, http://www.sdc-drr.net

Siebert A. (2000). Tools for risk catastrophe assessment in the insurance industry*, Proceedings of the ESRI International User Conference 2000 – San Diego,* retrieved 20.05.2012, http://proceedings.esri.com/library/userconf/proc00.

Siebert A. (2009). Globe of natural hazards. A new risk management tool*, Proceedings of the ESRI International User Conference 2009 – San Diego,* retrieved 20.05.2012, http://proceedings.esri.com/library/userconf/proc00.

Siegrist M., Gutscher H. (2006) Flooding risks: A comparison of lay people's perceptions and expert's assessments in Switzerland, *Risk Analysis* 26, 971-979.

Siegrist M., Gutscher H. (2008). Natural hazards and motivation for mitigation behavior: people cannot predict the affect evoked by a severe flood, *Risk Analysis* 28, 771-778.

Soeters R., Van Westen C. J. (1996). Slope instability regognition, analyisi, and zonation. In Turner A. K., Schuster R. L. (eds.) Landslides, investigation and mitigation, National Academy Press, Washington D.C., 129-177.

Skagg R. W., Khaleel R. (1982). Infiltration. In: Haan C.T., Johnson H.P., Brakensiek D.L. (eds.) *Hydrologic modeling of small watersheds,* American Society of Agricultural Engineers, St Joseph, Michigan, 121-166.

Slovic P., Finucane M., Peters E., Mac Gregor D. G. (2004). Risk as analysis and risk as feelings: some thoughts about affect, reason, risk and rationality, *Risk Analysis* 24(2), 311-322.

Smagorinsky J. (1963). General circulation experiments with the primitive equations, *Monthly Weather Review* 91, 99-164.

Smith R. E., Eggert K. G. (1978). Discussion of "Infiltration Formula Based on SCS Curve Number" by G. Aron, A. C. Miller, and D. F. Lakatos, *Journal of Irrigation and Drainage Division*, 462-464.

Smith K., Petley D. N. (2009). *Environmental hazards. Assessing risk and reducing disaster. 5*th Edition, Routledge, Oxon, New York.

Snyder F. F. (1938). Synthetic Unit Graphs. *Transactions of the American Geophysics Union* 19, 447-454.

SSDS (1993). *Soil survey manual*, Soil Survey Division Staff, Soil Conservation Service. U.S. Department of Agriculture Handbook 18, Washington D.C

Stehman S. V., Czaplewski R. L.(1998). Design and analysis for thematic map accuracy assessment: fundamental principles, *Remote Sensing of Environment* 64, 331-344.

Stehr N. (1996). *Knowledge as a capacity for action*, Science and technology redesign project, Statistics Canada.

Stelling G. S. (1984). *On the Construction of Computational Methods for Shallow Water Flow Problems*, Rijkswaterstaat Communications 35, The Hague.

Stelling G. S., Wiersma A.K., Wilemse J.B.T.M. (1986). Practical aspects of accurate tidal computations, *Journal of Hydraulics Engineers (ASCE)* 9(112), 802-816.

Su F., Hong Y., Lettenmaier D. P. (2008). Evaluation of TRMM multisatellite precipitation analysis (TMPA) and its utility in hydrologic prediction in the La Plata basin, *Journal of Hydrometeorology* 9, 622–640.

Syme W. J. (2001). TUFLOW – Two & one-dimensional Unsteady FLOW Software for Rivers, Estuaries and Coastal Waters, *IEAust Water Panel Seminar and Workshop on 2D Flood Modelling, Sydney, February 2001*, retrieved 24.08.2012, http://www.tuflow.com /download/publications.

Syme W. J. (2006). *2D or not 2D? An Australian perspective*, TUFLOW Papers, retrieved, 20.06.2012 www.tuflow.com/download/publications.

Syme W. J., Apelt C.J. (1990). Linked two-dimensional / one-dimensional flow modelling using the shallow water equations. *The institution of engineers Australia. Conference on hydraulics in civil engineering 1990. Sydney, 3-5 July 1990*, 28-32.

T – V

Taleb H. (2006) Water management in Morocco, in Dura G., Kambourova V., Simeonova F (eds.) *Management of intentional and accidental water pollution*, NATO Security through science series, Springer.

Taous A., Obda K., Amyay M., Laaouane M., Tribak A., Akdim A., Marques M. A., Furdada G., Julià R. (2010). Cartographie et zonage de l’aléa inondation à Taza (Maroc). Application de la “Méthode Géomorphologique Intégrée”, *Geomaghreb* 6, 1-19.

Tayefi V., Lane S. N., Hardy R. J., Yu D. (2007). A comparison of one- and two-dimensional approaches to modelling flood inundation over complex upland floodplains. *Hydrological Processes* 21, 3190-3202.

Thomi L. (2010). *Rôle des paramètres sociopolitiques et des connaissances dans la gestion des risques hydrologiques*. PhD thesis, University of Lausanne, 536p.

Tiscareno-Lopez M., Lopez V. L., Stone J. J., Lane L. J. (1993). Sensitivity analysis of the WEPP watershed model for rangeland applications, *Transactions ASAE* 36, 1659-1672.

Tobin G. A., Montz B. E. (1997). *Natural Hazards, explanation and integration*, The Guilford Press, New York.

UNDESA (2011). *Population distribution, urbanization, internal migration and development: an international perspective*, United Nations Department of Economic and Social Affairs, United Nations.

UNDP (2006). *Programme de réduction des risques de catastrophes au Maroc*. United Nations Development Program, New York.

UNISDR (2007). *Hyogo Framework for Action 2005-2015: Building the Resilience of Nations and Communities to Disasters. Extract from the final report of the World Conference on Disaster Reduction (A/CONF.206/6),* United Nations, International Strategy for Disaster Reduction, Geneva, 22p.

UNISDR (2009). *UNISDR Terminology. Disaster Risk Reduction*. United Nations International Strategy for Disaster Risk Reduction, United Nations, Geneva.

UNISDR (2011). *2011 Global Assessment Report. Revealing risk, redefining development*. United Nations publication,160p.

UNISDR (2013). Concept note. Information and Knowledge for Disaster Risk Reduction (IKM4DRR). Workshop at Global Platform 2013 and development of an IKM4DRR network, retrieved 3.06.2013, http://www.preventionweb.net, 5p.

USACE (2000). *Hydrologic modeling system HEC-HMS. Technical reference manual*, US Army Corps of Engineers, Hydrologic Engineering Center, Davis USA

USACE (2010). HEC-RAS *River analysis system. Hydraulic reference manual*, U.S. Army Corps of Engineers, retrieved 10.06.2010, www.hec.usace.army/mil.

Van Alphen J., Passchier R. (2007). *Atlas of flood maps. Examples from 19 European countries, USA and Japan*. Ministry of Transport, Public Works and Water Management, The Hague.

Van Mullem J. A. (1991). Runoff and peak discharges using Green-Ampt infiltration model, *Journal of Hydraulic Engineering*, 3(117), 354-370.

Varone F., Reynard E., Kissling-Näf I., Mauch C. (2002). Institutional resource regimes: the case of water management in Switzerland, *Integrated Assessment* 1(3), 78-94.

Verheye W., De la Rosa D. (2005). Mediterranean soils, in *Encyclopedia of life support systems (EOLSS)*, developed under the auspices of the UNESCO, Eolss Publishers, Oxford. Retrieved 20.12.2012, http://www.eolss.net.

Viglione A., Mertz R., Blöschl G. (2009). On the role of runoff coefficient in the mapping of rainfall to flood return periods, *Hydrology and Earth System Sciences* 13, 577-593.

Vinet F. (2008). Geographical analysis of damage due to flash floods in southern France: The cases of 12-13 November 1999 and 8-9 September 2002, *Applied Geography*, 4(28), 323-336.

Vischer D. L. (2003). *Histoire de la protection contre les crues en Suisse*, Rapports de l'OFEG, Série Eaux 5, Office Fédéral des Eaux et de la Géologie OFEG, Bienne.

W – Z

Wackermann G. (2004) *La géographie des risques dans le monde*, Paris, Ellipses.

Wagener T., Lees M. J., Wheater H. S. (2002). A toolkit for the development and application of hydrological models. In Singh, V.P. and Frevert, D.K. (eds.) *Mathematical* *models of large watershed hydrology*, Water Resources Publications LLC, Chelsea, Michigan, 91-140.

WBM Oceanics Australia (2007). TUFLOW (and ESTRY) user manual. GIS-based 1D/2D hydrodynamic modelling. Retrieved 20.06.2012, www.tuflow.com/downloads.

Wenger D. (2006). Hazards and disasters research : How would the past 40 years rate ? *Natural Hazards Observer* 31(1), 1-3.

Werren G. (2013). Mapping institutional vulnerability. A case study in Beni Mellal, Morocco. A possible application in Europe? In Arnaud-Fassetta G., Masson E., Reynard E. (eds.) *European continental hydrosystems under changing water policy*, 323-332 Verlag Dr. Friedrich Pfeil, Münich.

Werren G., Reynard E., El Khalki Y. (2013). Cartographie des phénomènes en vue de la réalisation de la carte indicative des dangers hydrologiques dans la ville de Beni Mellal, Maroc. Online document following the conference "La montagne marocaine : géomorphologie, environnement et développement", Beni Mellal, 5-6 may 2010.

Wheater H. S. (2002). Hydrological porcesses in arid and semi-arid areas. In Wheater H. S., Al Weshash R. S. (eds.) *Hydrology of wadi systems*, UNESCO, Paris.

White G. (1973). Natural hazards research. In Chorly R. (ed.) *Directions in Geography*, London.

Wilches-Chaux G. (1989). La vulnerabilidad global. In Maskrey A. (ed.) *Los desastres no son naturales*, LA RED, Lima.

Wisner B., Blaikie P., Cannon T., Davis I., 2004. *At risk. Natural hazards, people's vulnerability and disasters*. Routledge, London.

Yaalon D. H. (1997). Soils in the Mediterranean region: what makes them different? *Catena* 28, 157-169.

Yong, B., Hong Y., Ren L-L., Gourley J. J., Huffman G. J, Chen X., Wang W., Khan S. I. (2012), Assessment of evolving TRMM-based multisatellite real-time precipitation estimation methods and their impacts on hydrologic prediction in a high latitude basin, *Journal of Geophysical Research* D09108 (117), 1-24 (in press).

Young P., Parkinson S., Lees M. (1996). Simplicity out of complexity in environmental modelling: Occam's razor revisited, *Journal of Applied Statistics* 23, 165-210.

Yu D., Lane S. N. (2006). Urban fluvial flood modelling using a two-dimensional diffusion-wave treatment, part 1: mesh resolution effects. *Hydrological Processes* 20, 1541-1565.

Yu D., Lane S. N. (2011). Interactions between subgrid-scale resolution, feature representation and grid-scale resolution in flood inundation modelling. *Hydrological Processes* 25, 36-53.

Zaugg M. (2004). More space for running waters: negotiating institutional change in the Swiss flood protection system, *GeoJournal* 58, 275-284.

Zeino-Mahmalat E., Bennis A. (eds) (2012). *Environnement et changement climatique au Maroc. Diagnostic et perspectives,* Konrad-Adenauer Stiftung, Bureau au Maroc, Casablanca.

Zimmerman M., Pozzi A., Stössel F. (2005). *Vademecum. Hazard maps and related instruments. Experiences with the Swiss system and its adaptations abroad*, Swiss Agency for Development and Cooperation SDC, Berne, 34p.

Zimmermann M., Stössel F. (2011). *Disaster risk reduction in international cooperation: Switzerland's contribution to the protection of lives and livelihoods*, Swiss Agency for Development and Cooperation SDC, Berne, 24p.

Zhou J. G., Stansby P. K. (1999). 2D shallow water flow model for the hydraulic jump, *International Journal for Numerical Method in Fluids* 29, 375–387.

Zumstein J. (2010) : *Secouristes volontaires de proximité (SVP) – Maroc*, SDC, Berne, 1p.

Interviews with natural hazards practitioners in Switzerland

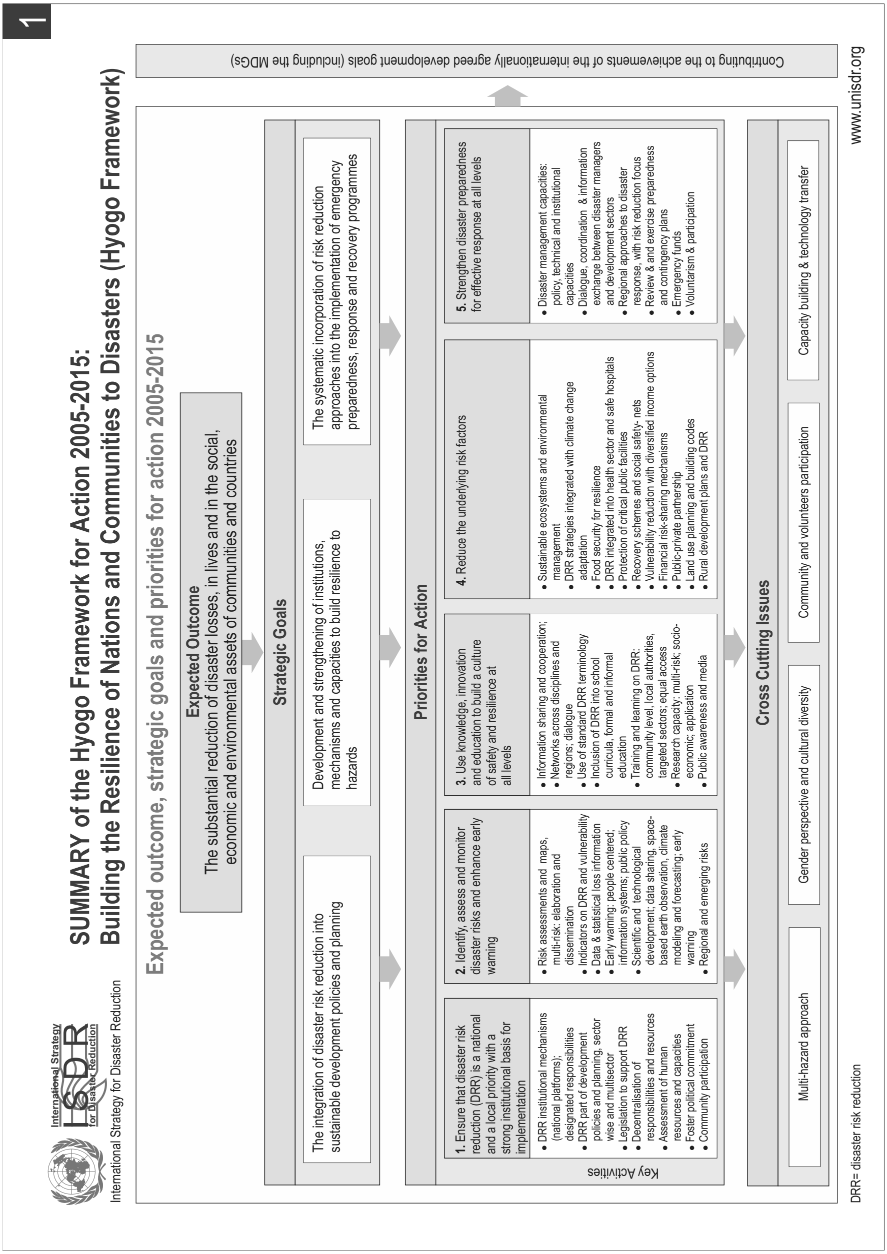
EB (2013). Eric Bardou, CREALP Engineers bureau, Valais

MZ (2013). Markus Zimmermann, NDR Consulting, Thun

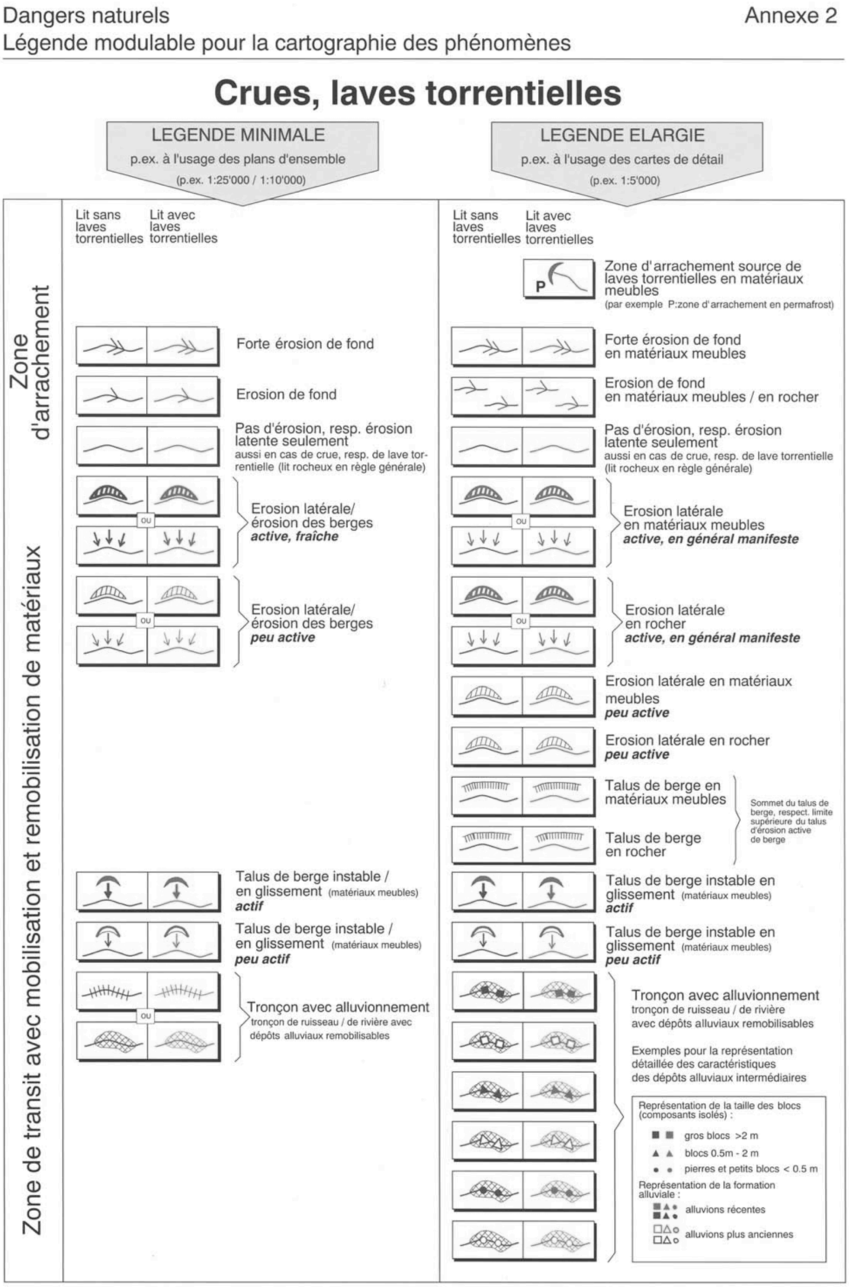
RG (2013). René Graf : Natural Hazards division, Canton of Lucerne

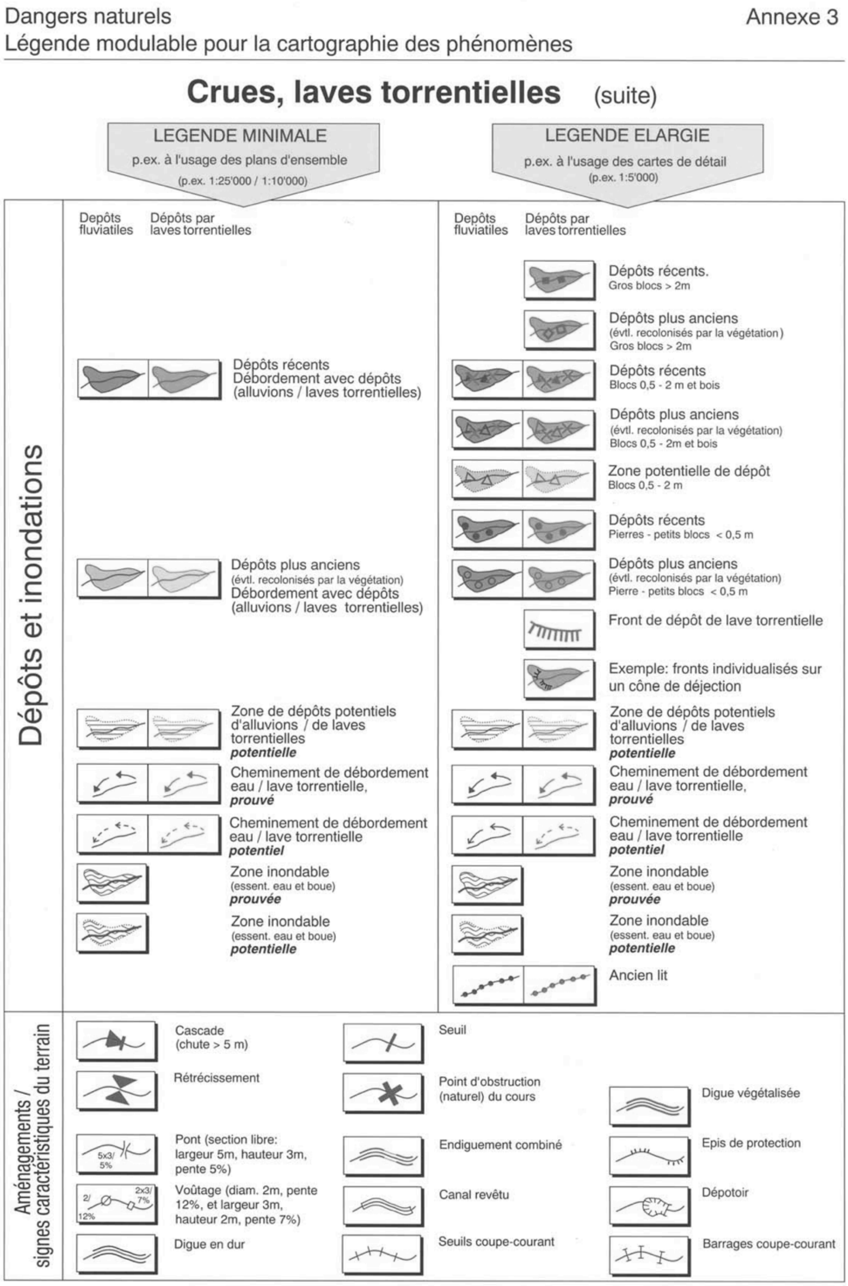
Appendices

Appendix 1. Summary of the Hyogo Framework for Action priorities (UNISDR 2007).

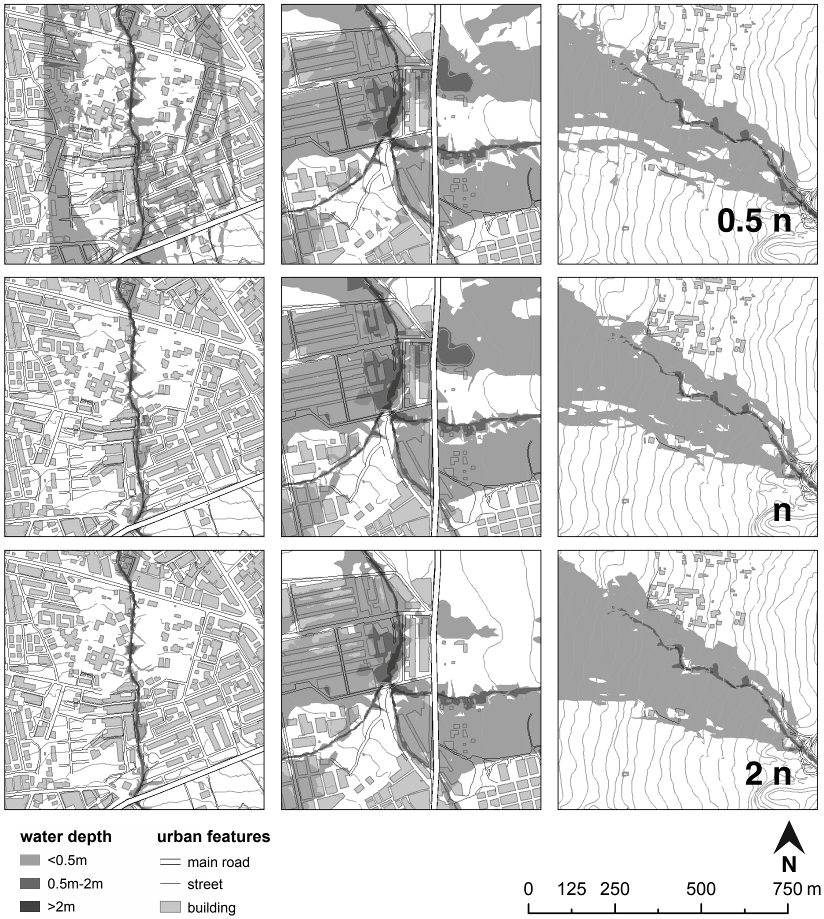


Appendix 2. Swiss adaptable legend for phenomena mapping: floods and debris flows. From Kienholz & Krummenacher (1995).

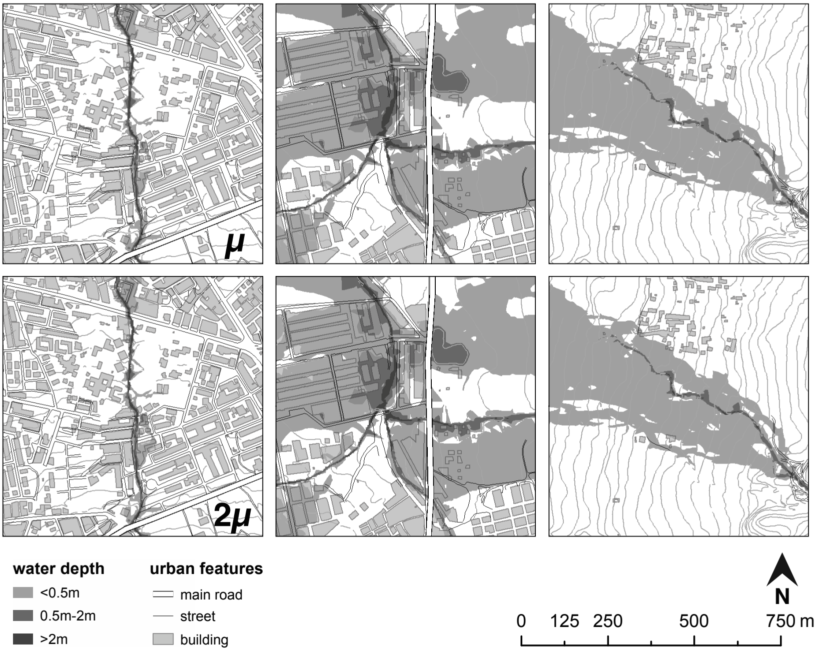



Dangers naturels
Légende modulable pour la cartographie des phénomènes
Annexe 3
Crues, laves torrentielles (suite)
LEGENDE MINIMALE
p.ex. à l'usage des plans d'ensemble
(p.ex. 1:25'000 / 1:10'000)
LEGENDE ELARGIE
p.ex. à l'usage des cartes de détail
(p.ex. 1:5'000)
Dépôts et inondations
Dépôts fluviatiles
Dépôts par laves torrentielles
Dépôts récents Débordement avec dépôts (alluvions / laves torrentielles)
Dépôts plus anciens (évtl. recolonisés par la végétation) Débordement avec dépôts (alluvions / laves torrentielles)
Zone de dépôts potentiels d'alluvions / de laves torrentielles potentielle
Cheminement de débordement eau / lave torrentielle, prouvé
Cheminement de débordement eau / lave torrentielle potentiel
Zone inondable (essent. eau et boue) prouvée
Zone inondable (essent. eau et boue) potentielle
Dépôts récents. Gros blocs > 2m
Dépôts plus anciens (évtl. recolonisés par la végétation) Gros blocs > 2m
Dépôts récents Blocs 0,5 - 2 m et bois
Dépôts plus anciens (évtl. recolonisés par la végétation) Blocs 0,5 - 2m et bois
Zone potentielle de dépôt Blocs 0,5 - 2 m
Dépôts récents Pierres - petits blocs < 0,5 m
Dépôts plus anciens (évtl. recolonisés par la végétation) Pierre - petits blocs < 0,5 m
Front de dépôt de lave torrentielle
Exemple: fronts individualisés sur un cône de déjection
Zone de dépôts potentiels d'alluvions / de laves torrentielles potentielle
Cheminement de débordement eau / lave torrentielle, prouvé
Cheminement de débordement eau / lave torrentielle potentiel
Zone inondable (essent. eau et boue) prouvée
Zone inondable (essent. eau et boue) potentielle
Ancien lit
Aménagements / signes caractéristiques du terrain
Cascade (chute > 5 m)
Rétrécissement
5x3/ 5%
Pont (section libre: largeur 5m, hauteur 3m, pente 5%)
2/ 12% 2x3/ 7%
Voûtage (diam. 2m, pente 12%, et largeur 3m, hauteur 2m, pente 7%)
Digue en dur
Seuil
Point d'obstruction (naturel) du cours
Endiguement combiné
Canal revêtu
Seuils coupe-courant
Digue végétalisée
Epis de protection
Dépotoir
Barrages coupe-courant

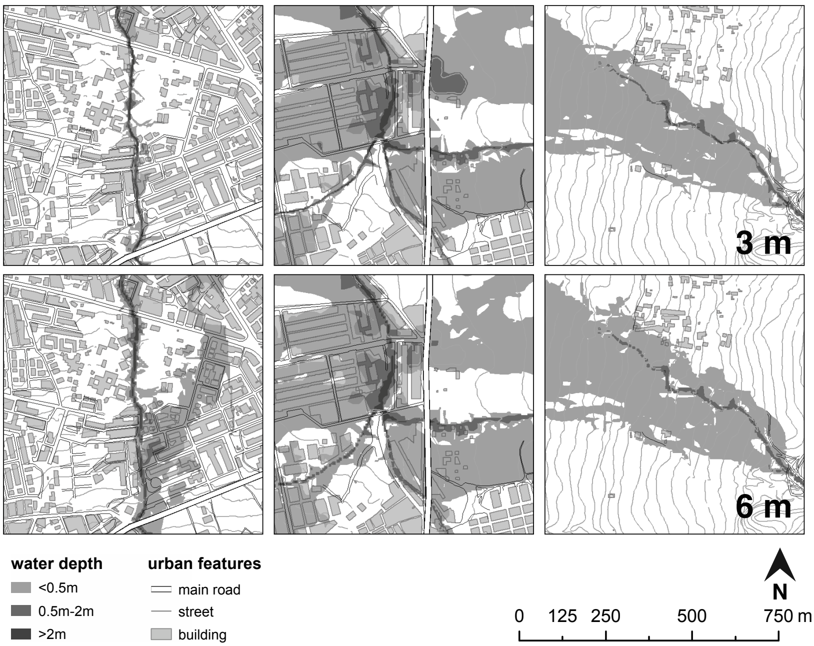
Appendix 3. Roughness and flood process representation (BM).



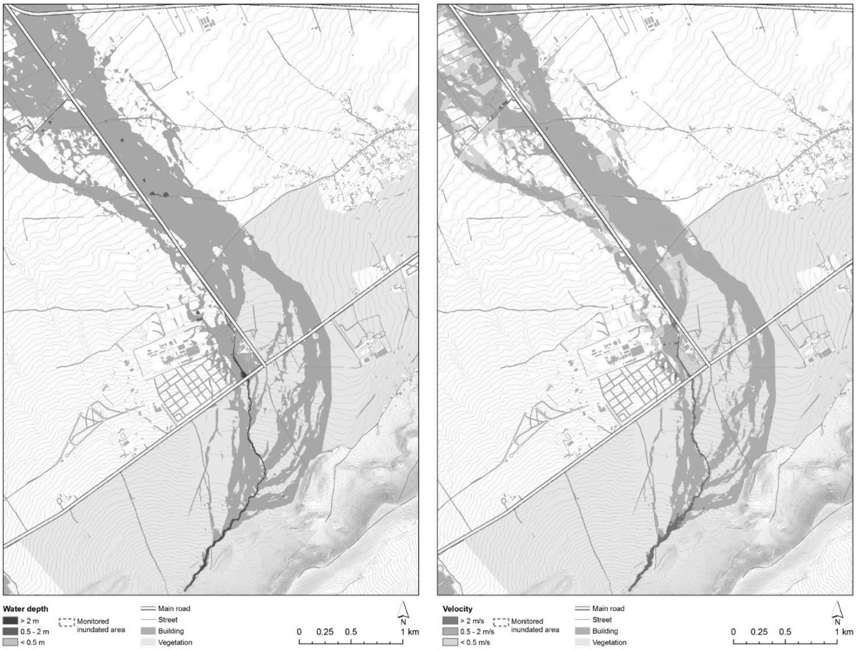
Appendix 4. Eddy viscosity and flood process representation (BM).



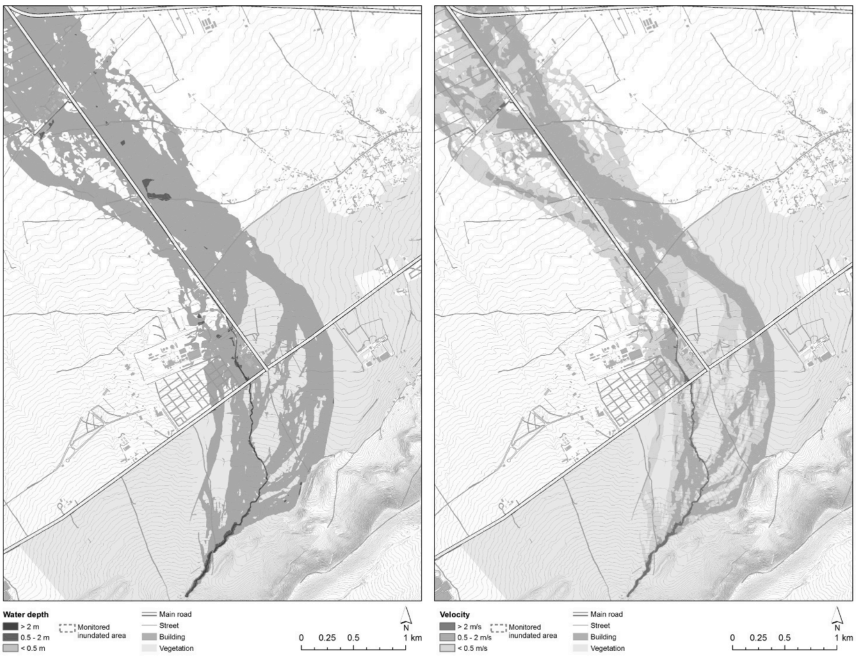
Appendix 5 Spatial resolution and flood process representation (BM).



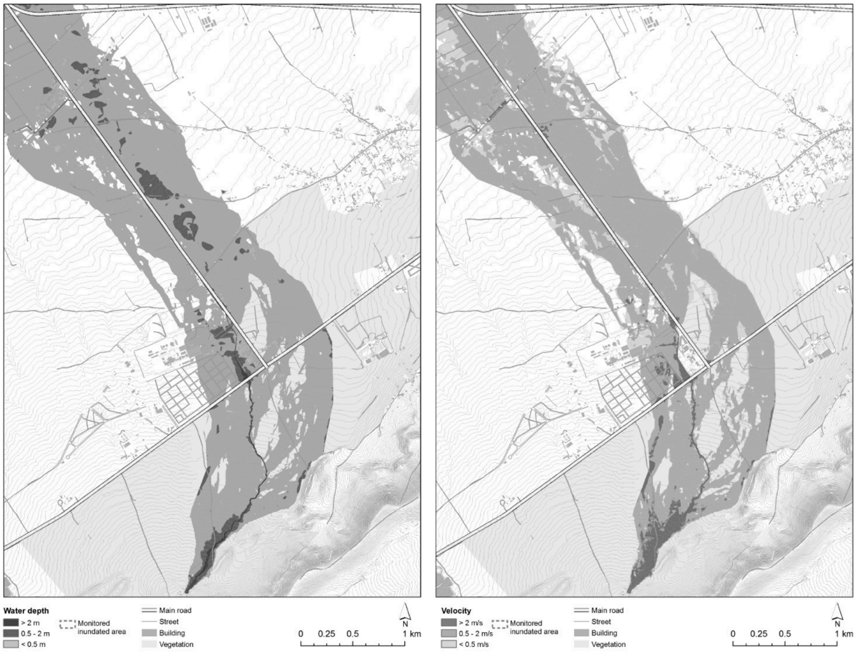
Appendix 6. Water depth and velocity simulation (KIK): 20-year event.



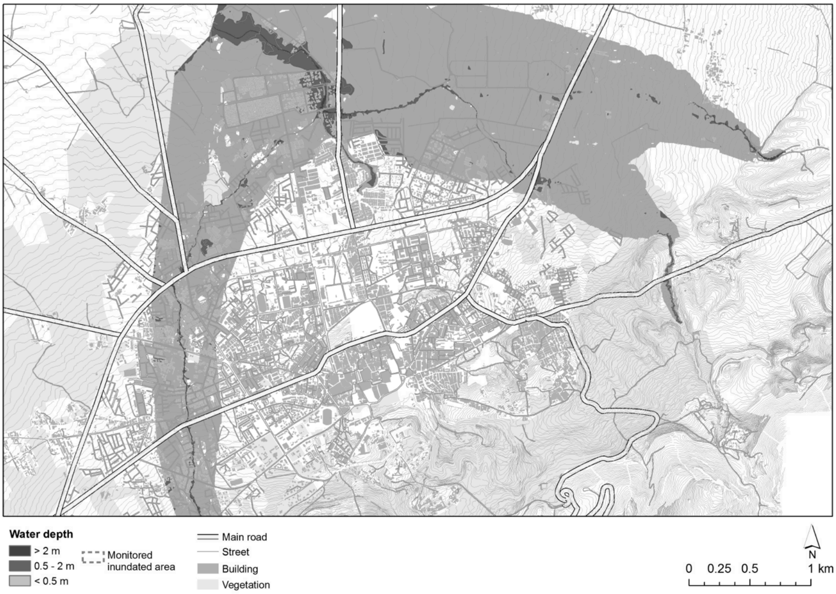
Appendix 7. Water depth and velocity simulation (KIK): 50-year event.



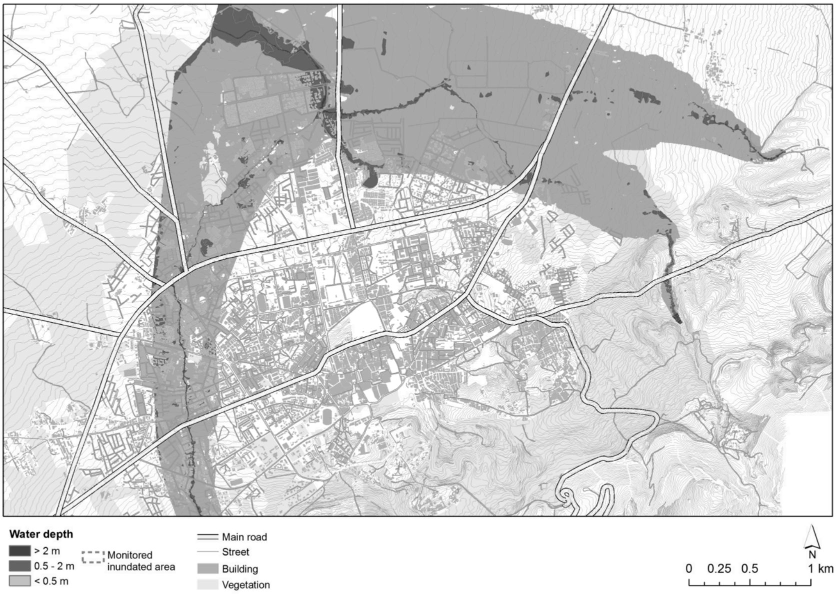
Appendix 8. Water depth and velocity simulation (KIK): 100-year event.

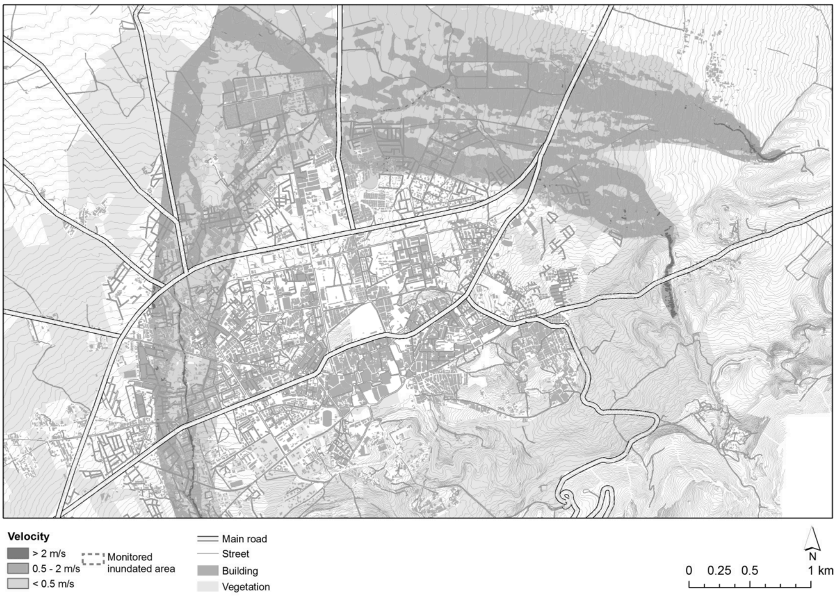


Appendix 9. Water depth and velocity simulation (BM): 20-year event.

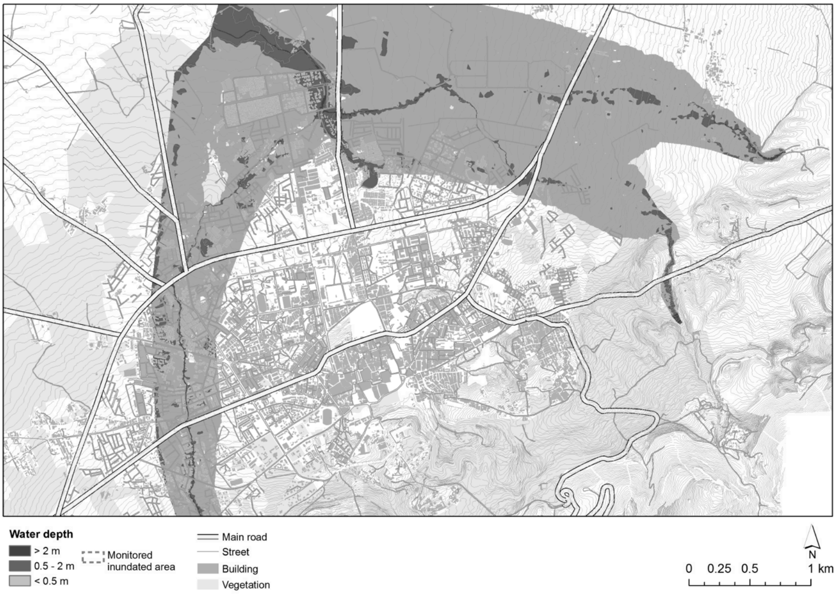


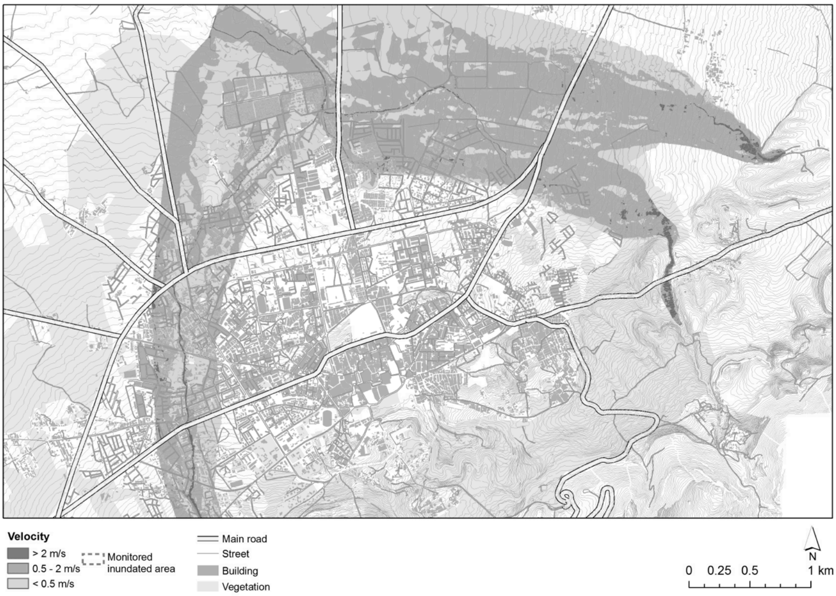
Appendix 10. Water depth and velocity simulation (BM): 50-year event.



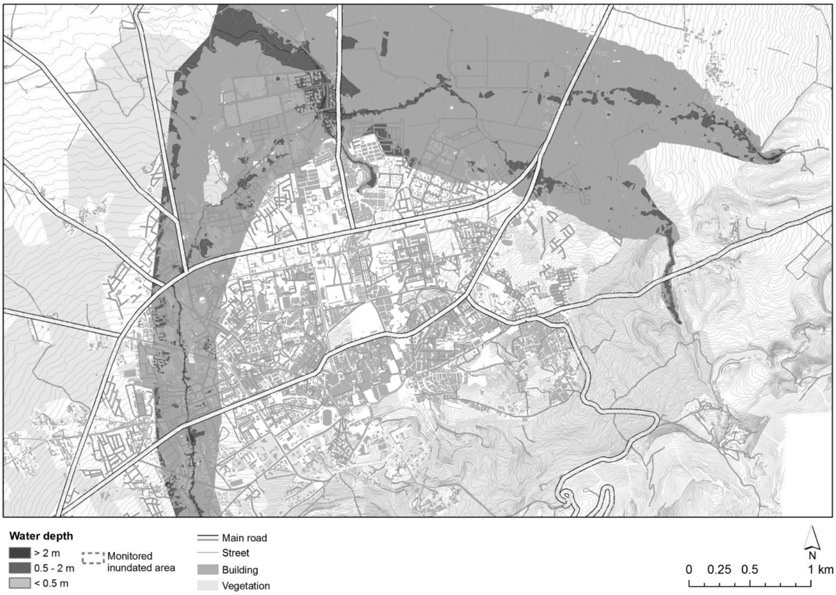


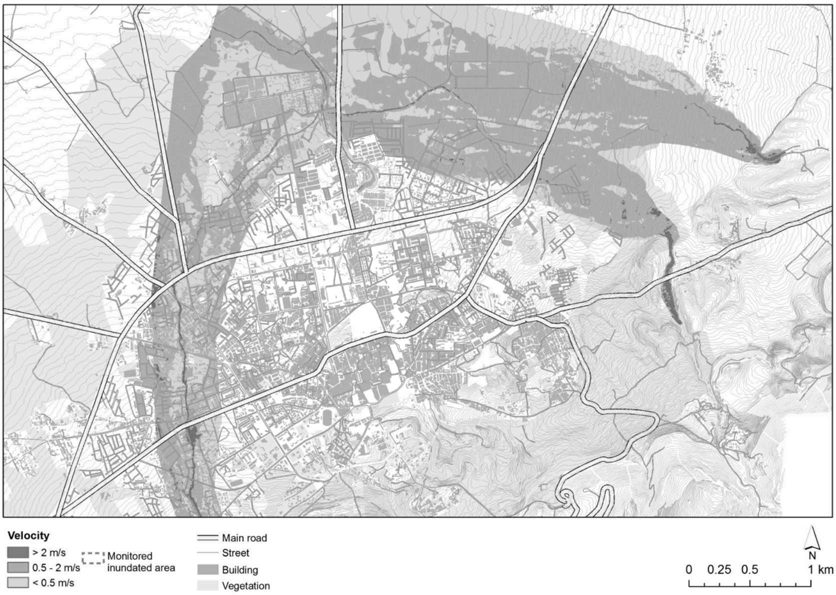
Appendix 11. Water depth and velocity simulation (BM): 100-year event.





Appendix 12. Water depth and velocity simulation(BM):100-year event, Handak dam effect excluded.





Appendix 13. Institutional vulnerability. Detailed semi-directive interview example.

Projet : « Gestion du risque d'inondation dans deux bassins versants marocains : Fès et Beni Mellal »

Entretien sur le rôle des acteurs institutionnels dans la gestion du risque

Date :
Institution :
Lieu : Beni Mellal
Interlocuteur : M.
Entretien no :
Fonction :

Appréciation du risque et mesures de précaution

A) Réglementation / Contrôle

1. Quels instruments juridiques pour la gestion du risque d'inondation au Maroc? Et à Beni Mellal ?

2. Comment le risque d'inondation est-il pris en compte par les S.D.A.U. ?

3. Qui met en oeuvre les prescriptions des S.D.A.U.?

4. Comment le risque d'inondation est-il pris en compte dans les Plans d'aménagement?

5. Qui met en oeuvre les prescriptions des plans d'aménagement ?

6. Quelle est l'imbrication de ces documents au niveau de la décision ?

7. Quels instruments de contrôle et d'intervention en cas de non-respect des prescriptions ?

8. Qui est responsable du contrôle et de l'intervention en cas de non-respect des prescriptions ?

B) Information / Connaissance du phénomène

9. Qu'est-ce que le risque ? Qu'est-ce que le risque d'inondation ?

10. Est-ce que le risque s'est modifié dans le temps ? Quels facteurs, quelles raisons à l'origine de ce changement ?

11. Quel type de connaissances liées au risque détenez-vous ?: scientifiques, juridiques, expérience personnelle…

12. Quels canaux d'information sont mis à disposition pour la population concernée ? journaux, prévention, etc…

13. Quelle relation avec les milieux scientifiques (université) en ce qui concerne la gestion du risque ?

14. Quelle relation avec les milieux professionnels (bureaux d'étude) en ce qui concerne la gestion du risque ?

C) Prévention

15. Qui s'occupe et comment est organisée la prévention des risques à Beni Mellal ?

16. Qui s'occupe de l'aménagement des cours d'eau?

17. Quels documents, directives, autorisations… gèrent la mise en oeuvre de ces aménagements ?

18. Qui construit les ouvrages de protection ?

19. Quels aménagements sont dans l'attribution directe de votre institution / département ?

20. Du point de vue spatial, à quel domaine (urbain, périurbain, bassins versants…) vos attributions s'étendent-elles?

21. Quels objets d'art ou techniques sont utilisés ?

22. Quels instruments ou mesures d'aménagement du territoire sont utilisés dans un but de prévention des risques d'inondation à Beni Mellal ?

23. Quels sont les services avec lesquels vous travaillez le plus souvent sur des questions de prévention des risques ?

24. Quel type de relation entretenez-vous avec ces services (hiérarchique, horizontale, etc)

25. Autres mesures : reforestation : quelle concertation avec les mesures de protection ?

26. Y a-t-il des directives concernant l'harmonisation des mesures ?

27. Cartographie du danger : quelle place dans la gestion du risque ? Avez-vous des expériences concernant la cartographie du danger ?

Maîtrise d'un évènement et rétablissement post-crise

A) Alerte / Intervention / Prévision

28. A quel niveau la prévision / alerte se fait-elle ? national, régional, local…

29. Quel seuil météorologique pour déclencher l'alerte ?

30. Quel temps d'intervention ?

31. Qui intervient une fois l'alerte donnée ?

32. Quel type d'actions sont entreprises ?

B) Reconstruction

33. Comment les mesures de reconstruction sont-elles organisées ?

34. Qui en est responsable ?

35. Quel rôle jouent les assurances dans le processus de rétablissement ?

36. Auriez –vous d'autres remarques ou compléments à faire?

Appendix 14. Summary: methodological and institutional recommendations.

Domain	Methodological	Domain	Institutional
General	**Data** quality and availability: need for: free access, precise data (DTM, climatic DB), denser gauging networks.	General	**Legal framework** for passive measures and hazard assessment implementation to planning.
	Need for **multidisciplinary** skills and collaboration.		**Generalize** hazard assessment and mapping.
	Adapt assessment to the context (hydro-climatic, morphologic).		**Enforce** danger maps and **implement** them to master plans.
			Control urbanization in hazard-prone areas.
Modelling	Need for thorough **field knowledge** and **holistic** approach.	RM*	Prioritize **passive** mitigation measures.
	Adapt model choice to data and context according to the parsimony principle.		Enforce hazard assessment to planning institutional **bond**.
	Use all sources of **data verification** (*phenomena* maps, airborne imagery, etc.).		Better coordinate active measures and avoid hazardous **side-effects** related to protection structures.
	Undertake a cost-effectiveness analysis when choosing models.		Better **define** responsibilities and roles in "normal" flood situations.
Mapping	Need for **unitary guidelines** for field surveys and geomorphic mapping.		Rethink rehabilitation in order to unburden local communities.
	Adapt map precision to data quality and inherent uncertainties.	KM*	**Educate** managers to the risk culture.
	Visually test danger map acceptance by stakeholders and the public		Use hierarchy to clearly **define roles** and responsibilities.
	Define **risk acceptance** within the community		Better **regulate** semi-formal **agreements** in order to innovate in risk management.
	Communicate risk concepts and enhance comprehension by end-users.		Open up to the **academia** for innovative and more integrative risk assessment and management solutions.
	Need for unitary guidelines for Assessment and cartographic rendering		

*RM = risk management; KM: knowledge management

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