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Master Thesis

Water Engineering

Flood Modeling and Floodplain Mapping Based on Geographical Information System (GIS) and HEC-RAS in Oued Fez Watershed (Morocco)

Scholar

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Certification

I undersigned, Prof. El Garouani Abdelkader, guest lecturer at the Pan African University of Water and Energy Sciences including Climate Change (PAUWES), and permanent lecturer at the Faculty of Sciences and Techniques of Fez (FST), Morocco; certify that Miss Astride Mélaine Adjinacou conducted her master thesis research under my supervision.

Supervisor's signature:

Scholar's signature:

Dedication

To Almighty God for his blessings….

Acknowledgement

The floodplain modeling and mapping in Oued Fez watershed based on Geographical Information System and HEC-RAS; is the result of a collective effort, built upon the contribution of several organizations and people. We would therefore like to express our gratitude to:

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Abstract

Maps give a more direct and stronger impression of the spatial distribution of the flood risk than other forms of presentation such as diagrams or verbal description. The urban flood risk appears among the major environmental preoccupations of actors in resources management and land planning; and this issue is exacerbated by the climatic and the global change factors. Flood, considered as one of the worst weather-related natural disaster, cause severe damages to life, properties and environment. For the floodplain mapping, we adopted an approach based on modeling of flows processes using US Army Corps of Engineers Hydrological Engineering Corporation's River Analysis System (HEC-RAS) model. The main sources of information are maps, hydro-meteorological data, Digital Elevation Model (DEM), satellite images, field observation, etc. This research presents a straightforward approach for processing input and output of the HEC-RAS hydraulic model, to enable two and three dimensional floodplain mapping and analysis in the ArcGIS environment. The hydraulic modeling tool HEC-RAS is used to perform the steady flow simulations and the model input files are developed in the ArcMap environment by using the software extension HEC-GeoRAS. The study area concerns Fez located in Saiss plain. The agglomeration of the city is actually being developed in the area of confluence of all the hydrologic network of Oued Fez watershed. This watershed, which is composed of several sub-basins, receive its water from six essential Oueds. The results of the study indicate furthermore that Geographic Information System is an effective environment for floodplain mapping and analysis. The resulting GIS maps, consisting of flood hazard, floodplain extension and risk maps. This helpful information can guide the local early warning system of flood and identify the areas facing flood risks.

Key words: Floodplain mapping, Hydraulic modeling, ArcGIS, HEC-GeoRAS, Fez, Morocco

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General Introduction & Objectives of the study

General Introduction

Floods are probably the worst weather-related natural disaster, widespread, disastrous and frequent natural hazards of the world (Rajiv, 2005); which cause severe damages to life, properties and environment. Over the last 30 years (1981–2011), floods have been the most recurrent disasters recorded in EM-DAT, with at least 300 events (53 percent of the total number of disasters), indicating a strong need for early warning systems[1]. This large increase can be attributed to a growing concentration of assets at risk, particularly in urban areas, and insufficient structural and non-structural mitigation measures (World Bank, 2014).

In Africa only, flood is the number one hazard in terms of frequency and impact in the subcontinent - almost 50 % of disasters are floods (Ouikotan et al. 2015). Beyond that, the Intergovernmental Panel on Climate Change (IPCC) assumes that there will be an average of temperature rise in the 21st century (1.4 to 5.8 degrees Celsius). Based on this assumption, the sea is expected to rise (9 cm to 88 cm by the year 2100). The precipitation pattern will also change. Humid areas will generally become more humid, and arid areas more arid. In general, this means a greater probability of flooding and extremely low rivers during dry periods.

Besides that, according to Action aid (2006), flood hazards are natural phenomena, but damage and losses from floods are the consequence of human action. Urbanisation aggravates flooding by restricting where flood waters can go, covering large parts of the ground with roofs, roads and pavements, obstructing sections of natural channels and building drains that ensure that water moves to rivers faster than it did under natural conditions. As more people crowd into cities, so the effects intensify. As a result, even quite moderate storms produce high flows in rivers because there are more hard surfaces and drains. The impact of flooding can be particularly severe in peri-urban agricultural areas. The harvest will be damaged and the country will have to resort to international food aid. In more general terms, flooding increases the incidence of malaria, and can expose the population to toxic substances, harms health, and increases requests for medical assistance. The impact of flooding on people’s livelihoods and goods is potentially huge if settlements are not protected from high water, if they have been constructed in dry riverbeds or if the population has not been warned of the risk of high water with enough warning. Flooding also affects people who are outside the flooded area and directly or indirectly use the affected facilities. Consequently, another severe impact concerns transport infrastructure such as roads and railways. Their paralysis stops all economic trade, and if petrol distribution is hindered as a result, interruptions in the electricity supply may also occur.

However, while around the world, the number of disasters has almost doubled since the 1980s, in the MNA (Middle East and North Africa) region where Morocco belongs, the average number of natural disasters has almost tripled over the same period. Approximately 40 million people have been affected by over 350 natural disasters between 1981 and 2010, according to EM-DAT. The most frequent disasters in the region are floods (considered number one in term of damage), earthquakes, storms, and droughts. In Morocco especially for instance,

[1] UNISDR, *Global Assessment Report on Disaster Risk Reduction*

during the months of December 1995 and January, February and March 1996, the Atlantic coastline of the Kingdom was hit by successive waves of torrential rain which caused severe flooding[2]. According to the Ministry of the Interior, some 60, 000 people were directly affected by the flooding, with a number of deaths being registered. Many Shantytowns were devastated and several thousand hectares of agricultural land inundated. Another examples include violent storms in November 2014 which have caused widespread flooding and flood several wadis in a large part of the south of the Kingdom. The storms were still ongoing late afternoon of Sunday 23 November and an awareness bulletin remained in effect until Monday noon (24 November) according to the national meteorology. In total there were 36 deaths, two missing and 500 rescued. At least 140 houses of adobe were destroyed and 100 roads were cut off including 6 national highways (EPoA, 2014). To add on that, in December 2009, floods caused by heavy rains have killed five people, injured 20 and left many thousands homeless in and around Moroccan town of Agadir. 1,500 families were estimated to have been affected by the worst floods the region has been experiencing since decades (DREF, 2010).

Since five decades, the flooding risks have been intense in the Fez agglomeration (Morocco). Their impacts were important either inside the urban area or in its immediate peripheries, where population densities are progressively high. The south-eastern Fez suburbs experienced episodic flooding risks since 1950. A severe flood disaster occurred in 1989, when Oued Boufekrane frightened the extending habitat in its valley bottom and engendered several human victims. In October the 12th, 2008 an abrupt rise of the Oued discharge caused considerable material loss in the area.

Those figures alone render consideration of flood risk management, a necessity, especially in this context of climate change which, according to Action Aid (2006), will increase the vulnerability and damages in the countries. . With respect to that, the prevention of the risk could be a positive point for the management of the disaster. Conjointly, according to Merz et al, (2006), one of the cornerstones of flood risk management is the information of people at risk and of the authorities and agencies responsible for flood management. Only if the people and decision makers are aware of the flood risk, and only if they are able to evaluate the risk, they can then be expected to adequately respond to this thread[3]. Additionally, owing to the fact that maps give a more direct and stronger impression of the spatial distribution of the flood risk than other forms of presentation such as diagrams or verbal description (Merz et al, 2006); this work will focus on **Flood Modelling and Flood plain Mapping based on Geographical Information System in Fez watershed in the Kingdom of Morocco**.

Owing to that, the study sets out to achieve three specific goals:

Objectives of the study

- Assess factors controlling flood hazards in the study area
- Conduct the hydraulic simulation of flood in the watershed

[2] Kingdom of Morocco : floods/ appeal no. 02/96 Situation report no 2 (Final report)
[3] Thieken, 2006

- Develop the indicative maps of flood risk in the study area and recommend some mitigation and/or adaptation measures to reduce the impact on people and the environment

To achieve these goals, the work will be subdivided in 5 chapters. The chapter 1 will focus on the flood risk assessment and the factors controlling flood hazard in the city of Fez. The same chapter will encompass in addition the review of the flood risk models. In the chapter 2, the study will present Oued Fez watershed, its physiographic and climatic characteristics. The chapter 4 will focus on the modeling and the mapping of the flood in the study area; and the results will be presented and discussed in the fifth chapter. The general conclusion followed by some recommendations will be treat lastly.

Chapter I: Floods risk assessment and factors controlling flood hazards

Flood assessment and different types of flood in Fez

Flood risk assessment: Hazard, Vulnerability and Risk

Factors controlling flood hazard in Fez

This chapter sheds light on the different types of floods existed with a focus on Fez agglomeration.

1.1- Flood assessment and different types of flood in Fez

1.1.1- Flood: definition and types

Flood can be represented as a temporary covering by water of land normally not covered by water. There are several different types of floods. Most communities experience only a few of them. Each kind of flood bears a different impact in terms of how it occurs, the damage it causes and how it is forecasted. Floods are generally grouped into the following types:

- Riverine flooding
- Urban drainage
- Ground water flooding
- Fluctuating lake levels
- Coastal or marine flooding and erosion

1.1.2- Riverine flooding

The dynamics of riverine (fluvial, river) flooding vary with terrain. In relatively flat areas, land may stay covered with shallow, slow-moving floodwater for days or even weeks. In hilly and mountainous areas, floods may come minutes after a heavy rain. This type of flood occurs when excessive rainfall over an extended period of times causes a river to exceed its capacity. It can also be caused by heavy snow melt and ice jams. The damage from a river flood can be widespread as the overflow affects smaller rivers downstream, often causing dams and dikes to break and swamp nearby area. Among the common types of riverine flooding are: overbanking flood, flash floods, dam and levees failures, alluvial fans, ice jam flooding and moveable bed streams (Maddox, 2014).

Overbanking flooding occurs when water rises overflows over the edges of a river or stream. In another words, it is the increase in volume of water within a river channel and the overflow of water from the channel onto the adjacent floodplain. Overbanking flooding represents the classic flooding event that most people associate with the term “flood.” Actually, this is also the most common type of flood event and can occur in any size channel, from small streams to huge rivers.

Furthermore, the World Meteorological Organization defines flash flood as a rapid onset flood of short duration with a relatively high peak discharge. According to the American Meteorological Society it as a “…flood that rises and falls quite rapidly with little or no advance warning, usually as the result of intense rainfall over a relatively small area.” Generally, flash flood can be characterized by an intense, high velocity torrent of water that occurs in an existing river channel with little to no notice. Flash floods are said to be very dangerous and destructive not only because of the force of the water, but also the hurting debris that is often swept up in the flow. In addition to that, the greater the precipitation intensity, the more likely it is that significant surface runoff will be generated. Higher precipitation intensity can result in more runoff because the ground cannot absorb the water quickly enough. Although prior ground saturation increases the flash flood risk, many flash floods occur when the ground is not saturated. Flash floods can and do occur with dry soils and drought conditions. For instance, flash flood on November 2014 caused widespread flooding in large parts of southern Morocco, killing 47 people (IFRC, 2015). Thousands of adobe houses were destroyed and more than 100 roads were cut by the flood waters. A cold wave struck the affected communities from the first week of December and Agadir, Sidi Ifni, Tiznit and Bouizakarne provinces were affected by further flooding that left them isolated and inaccessible with a minimum of 3,000 families left in need (IFRC, 2015).

Moreover, like flash floods, flooding on alluvial fans can cause greater damage than typical riverine flooding due to the high velocity of water flow, the amount of debris carried, and the broad area affected by floodwaters. Alluvial fans, which occur mainly in dry mountainous regions, are deposits of rock and soil that have eroded from mountainsides and accumulated on valley floors in a fan-shaped pattern. The deposits are narrow and steep at the head of the fan, broadening as they spread out onto the valley floor. Fans provide attractive development sites due to their commanding views, but harbour severe flood hazards along with unique behaviour. Channels along fans are not well defined and flow paths are unpredictable. As rain runs off steep valley walls, it gains velocity, carrying large boulders and other debris. When the debris fills the runoff channels of the fan, floodwaters spill out, spreading laterally and cutting new channels. The process is then repeated, resulting in shifting channels and combined erosion and loading problems over a large area.

What is more is that some of the most significant losses due to the failure of flood control structures can be attributed to the construction of inadequate dams and levees or to a flood that exceeds the design protection level. Dam failure can often be traced either to a poor decision made during design and construction or to inadequate maintenance or operational mismanagement. Failure may also result from natural hazards, such as earthquakes, or from flow volumes that exceed capacity.

Besides that, Flooding caused by ice jams is similar to flash flooding – the formation of a jam results in a rapid rise of water both at the point of the jam and upstream. Failure of the jam results in sudden flooding downstream. The formation of ice jams depends on both the weather and the physical conditions in the river channel.

With respect to streambeds, its movement is most common where steep slopes and the lack of vegetation result in a lot of erosion. During a flood, a new channel may be created by erosion or an existing channel may fill in with sediment. Moveable bed streams are most common in mountainous areas.

The severity of a river flood is determined by the amount of precipitation in an area, how long it takes, for precipitation to accumulate, previous saturation of local soils, and the terrain surrounding the river system.

1.1.3- Urban drainage flood

Urban floods can be caused by flash, river or coastal flooding but most commonly, it is caused by high rainfall rates over developed areas that do not have the ability to absorb the water

(Maddox, 2014). Urbanization can increase water runoff as much as 2 to 6 times over what would occur on natural terrain. These floods can cause high economic damages to businesses and homes.

1.1.4- Ground water flooding

Groundwater flooding is more complex than surface water flooding as it depends upon the underlying geology, rainfall and antecedent groundwater levels. To generate groundwater flooding there has to be very high prolonged (extreme) rainfall combined with initially high groundwater levels in areas geologically predisposed to groundwater flooding (EXCIMAP 2007). Groundwater responds to rainfall more slowly than rivers, and only prolonged rainfall results in significant groundwater flooding

1.1.5- Coastal (surge flood or marine flood)

A coastal flood, according to Maddox (2014), occurs in areas that lie on the coast of a sea, ocean or other large body of open water. It is typically the result of extreme tidal conditions caused by severe weather. Storm surge is the leading cause of coastal flooding and often the greatest threat associated with a tropical storm. In this type of flood, water overwhelms low lying land and often causes devastating loss of life and property. Moreover, Maddox categorized coastal flooding in three different levels known as minor, moderate and major. The flood is minor when a slight amount of beach erosion will occur but no major damage is expected. In the case when a fair amount of beach erosion will occur as well as damage to some homes and businesses, the coastal flooding is said to be moderate. Finally, it is major when large scale beach erosion will occur accompanied by serious threat to life and property. Numerous roads will be flooded, and many structures will be damaged. Besides that, the severity of coastal flood is determined by several factors, including the strength, size, speed and direction of the storm. The onshore and offshore topography also plays a crucial role.

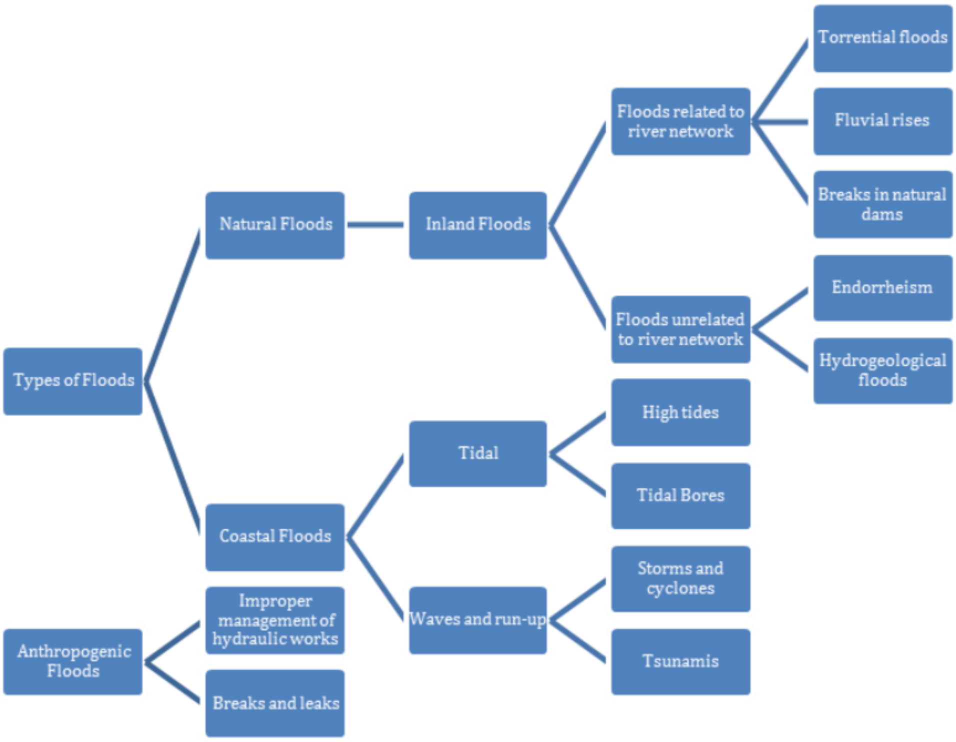


Figure 1: Types of floods (Wright, 2015)

1.2- Types of flood occurred in Fez

As far as our study area is concerned, five different types of inundation can be noticed such as:

- Ground water flooding
- Alluvial plain flooding
- Torrential flooding
- Inundation due to punctual overflow
- Urban runoff flooding

The first type mentioned is caused by ground water outcrop; which often follow an abundant and prolonged rainfall. That can load the water table and create overflow. That kind of flooding is qualified as slow and is not risky for people but it occasioned considerable damage to goods. The Saiss plateau is characterised by a deep Liassic table. On top of it, the Pliocene – Quaternary ground water is located at few meters of the plateau. During extended rainfall events on the oued Fez watershed, the ground water overflow at the upstream of the watershed. From 2008 to 2013 observations, the March 2010 flooding events were the most impressive because of the extended and prolonged rainfall events occurred between September 2009 and March 2010 on the watershed; with 740 mm in 7 months, recorded at the Fez – Saiss station. Those overflow, exacerbated by El Himmer and Ain Smen floods occasioned extensive flooding which exceeded 2 km of width in some streams of the basin. Sixteen (16) families were left without shelter in Douar Mchraa Kraym district and some houses were partially destroyed due to that flooding which last for several weeks. In addition, road traffic was disturbed. (Lasri, 2013).

Photo 2: Douar Mchraa Kraym inundation in Fez March 17th

Photo 1: Partial destruction of a house in Douar Mchraa Kraym

According to Alluvial flood inundation or floodplains, they can exceed 200 m of width is some El Himmer streams but with low depth and velocity. This type of floods characterise small alluvial plain of Oued El Himmer and downstream of Ain Smen watershed. Those plains have been created thanks to the successive deposit or filling of floods since the beginning of the quaternary after the emptying of the Saiss Lake (Martin, 1981; Fassi, 1999; Chapond et al, 1967; Taltasse, 1953 in Lasri 2013).

Concerning torrential floods, they are most often generated by Oueds Boufekrane, El Mehraz, upstream of Ain Smen and downstream of Oued Fez, at the entrance of the medina of Fez. This category of flood is the most devastating and represents a real danger to the life of the people because of the exceptional flood velocity; favoured by the slope of the oueds previously mentioned. The torrential inundations does not fill a large width but the water height can be considerable.

Photo 3: Torrential flood in Oued Fez at the medina in May 18th, 2011 with 4 m of height

What is more, inundation due to punctual overflow is occasioned by hydraulics structures (bridges, drainage canal) not well or less dimensioned and/or clogged.

Photo 4: Overflow of El Himmer drainage canal in Lala Soukaina district March 13th, 2013

Photo 5: Overflow of Oued Boufekrane drainage canal at the entrance of the medina of Fez in September 28th, 2008

Besides that flooding occasioned by urban runoff in Fez is due to the impermeability of the urban surface of the city. Actually, impermeability help in the increase of quick runoff of the flood. Scarwell and Laganier in 2004 mentioned that the runoff volume can increase from 500%

to 800%, according to the degree of impermeability. That led to small time of concentration and high peak discharge. Therefore the inundations amplified as it is the case sometimes in Fez agglomeration. For instance, on May 18th, 2010; the city received 52 mm of rainfall and all the neighbourhoods of the city have been inundated (Lasri, 2013).

The table below summarise the different type of flooding in the city of Fez, their time of occurrence and the damage their occasioned:

Table 1: Types of flooding occurred in Fez

Typology	Watersheds	Date	localities affected	Impacts or damages
Rise of the water table	Upstream of oued Fez	September and October 2008, September and March 2010, September 2001, March, 2013	Douar Mchraa Kraym, Hay Sitou, Doukkarat industrial neighbourhood	Destruction of mud houses, families left without shelter, long time of submertion, traffic road disturbance
floodplains	El Himmer, downstream ofAin Smen	September 1950, October 1989, Sepetember 2008, September 2010, December, 2010, March 2013	Lala Soukaina, El Merja, hey Tazi, Zougha, Seigrouchni, Ain Chkeff	Houses inundated , road traffic disturbance
Torrential floods	Oued Boufekrane, El Mehraz, Upstream of Ain Smen, downstream of oued Fez	September 26th, 1950, October 13th, 1989; September 28th, 2008	Monfleuri 1 & 2, Narjiss, Sidid Brahim, Lido, Aouinat El Haijaj	Destruction of houses and bridges, erosion, people at risk

Punctual overflow	Boufekrane and Mehraz oueds	September 1950; October 1989, September 2008	Bab Jdid at the entrace of the medina, Narjiss on Sefrou road	Clogged of bridges, traffic road disturbance
Urban runoff		Several events	Several localities	Destruction of houses, bridges, traffic road disturbance…

1.3- Flood process

1.3.1- Rainfall – runoff process

Rain is in general, the primary cause of most flood events. Surface runoff, and the consequential rapid inflow to streams, drainage channels or rivers, is determined by the rainfall-runoff process. The 'effect' of this part of the chain (surface runoff) is reduced by the removal of water as it falls to the ground by a number of factors including: interception (determined by vegetation type and coverage); infiltration to the soil (and subsequent absorption and transpiration by vegetation, percolation down into aquifers, or delayed contribution to surface water discharges); evaporation to the atmosphere (determined by atmospheric conditions).

1.3.2- Flow attenuation process

Once water has reached a watercourse through the rainfall-runoff process, it is incorporated with the existing flow in the channel from contributing areas upstream to produce the net flow at that point. The relationship of flow against time at a given point as the flood passes is described as a flood hydrograph. As a flood moves down the river it is subject to a series of influences that change the characteristics of the flood hydrograph, such as the timing and magnitude of the peak. In the absence of any additional inflows, the peak of the hydrograph will occur later due to the time taken for the flood to move downstream, and the magnitude of the flood peak will reduce due to temporary storage effects in the channel and floodplain. This process is known as attenuation. This process can be influenced in a number of ways by human activity such as localised drainage, channel maintenance or floodplain defence.

1.4- Flood risk assessment: Hazard, Vulnerability and Risk

1.4.1- Flood Hazard

A natural hazard is a potentially damaging physical event, phenomenon or human activity, which may cause the loss of life or injury, property damage, social and economic disruption, or environmental degradation (UNISDR, 2004). "Potentially damaging" means that there are elements exposed to the hazard that could, but need not necessarily, be harmed (Gouldby & Samuels, 2005).

According to Wright (2015), the relationship between the probability of a flood and its intensity gives rise to the concept of return period (T). A T-year flood is the flood intensity that has a probability of 1/T of being exceeded in a given year. This probability is called the exceedance probability. For example, there is an exceedance probability of 1/10 (0.10) that in a given year there will occur a flood larger than the 10-year flood intensity. Flood hazard assessments usually aim to estimate the flood intensity for a range of exceedance probabilities, for example from 0.1 to 0.001. Flood hazard is then defined as the exceedance of probability of potentially damaging flood situations in a given area and within a specified period of time. An example of a flood hazard statement is the flood frequency curve at a discharge gauge, giving different discharges and their associated exceedance probability. Flood hazard statements do not convey information about the consequences of such floods on society, built environment or natural environment. Since these consequences depend, among others, on the intensity of the flood, flood hazard statements should quantify the intensity of the process that go beyond a flood frequency curve (Merz et al, 2006).

Beyond that, the most prevalent indicator for the intensity of a flood is the inundation depth. Different studies identified the water depth as the flood characteristic which has the biggest influence on flood damage (Penning-Rowsell et al., 1994, Wind et al., 1999). Therefore, the discharges from a flood frequency curve are commonly transformed into inundation scenarios. Besides that, another important criterion for the flood intensity is flow velocity. Especially floods in mountainous areas may have high flow velocities which can lead to dramatic damages to buildings, infrastructure etc. For instance, in the Ore Mountains in August 2002 high flow velocities completely destroyed many buildings. Further, damage to human increases with velocity: people may be swept away when flow velocities are above 0.5 m/s (Marco, 1994). However, a better indicator for human instability in flood situations is the product of flow velocity v and water depth h. Other indicators for flood intensity are the duration of the flood situation and the rate of the water rise. (Merz et *al., 2006*). The rate of the water rise determines the time that is available for flood defence measures in case of a flood warning. In many cases failure of river levees is also influenced by the duration of the flood water level. Further flood characteristics that may influence the extent of the damage are the concentration and size of sediment and other transported material like driftwood, or the pollution load of flood waters. For example, the flood-induced contamination with heating oil may lead to complete damage of inundated buildings. These characteristics are rarely shown on flood maps since the quantification of the spatial and temporal distribution of such characteristics dramatically increases the requirements on data and models.

Besides that, flood plain maps indicate the geographical areas, which could be covered by a flood according to one or several probabilities: floods with a very low probability or extreme events scenarios; floods with a medium probability (likely return period >= 100y); floods with a high probability. Flood hazard maps are detailed flood plain maps complemented with: type of flood, the flood extent; water depths or water level, flow velocity or the relevant water flow direction. Flood hazard maps alone serve many purposes. They can be directly implemented (e.g. in land use planning processes), but are also the main input for vulnerability and risk maps and serve for the production of various end-user instruments. Additionally, three different approaches to develop flood hazard maps are historical approach, geomorphological approach and modelling approach. This later will be used in this study.

1.4.2- Vulnerability

Vulnerability is the degree of fragility of a (natural or socio-economic) community or a (natural socioeconomic) system towards natural hazards. It is a set of conditions and processes resulting from physical, social, economic and environmental factors, which increase the susceptibility of the impact and the consequences of natural hazards (Samuels, 2009). Vulnerability is determined by the potential of a natural hazard, the resulting risk and the potential to react to and/or to withstand it, i.e. its adaptability, adaptive capacity and/or coping capacity.

1.4.3- Flood Risk

Flood risk is defined by Jose (2008) as the combination of the probability of a flood event and of the potential adverse consequences to human health, the environment and economic activity associated with the flood event. In addition and according to the Flood Directive, (EU, 2007), the most common approach to define flood risk is the definition of risk as the product of hazard, i.e. the physical and statistical aspects of the actual flooding (e.g. return period of the flood, extent and depth of inundation), and the vulnerability, i.e. the exposure of people and assets to floods and the susceptibility of the elements at risk to suffer from flood damage. Apel et al (2008) laid flood risk out, as the probability that flood of a given intensity and a given loss will occur in a certain area within a specified time period. Consequently, flood risk results from the interaction of hazard and vulnerability.

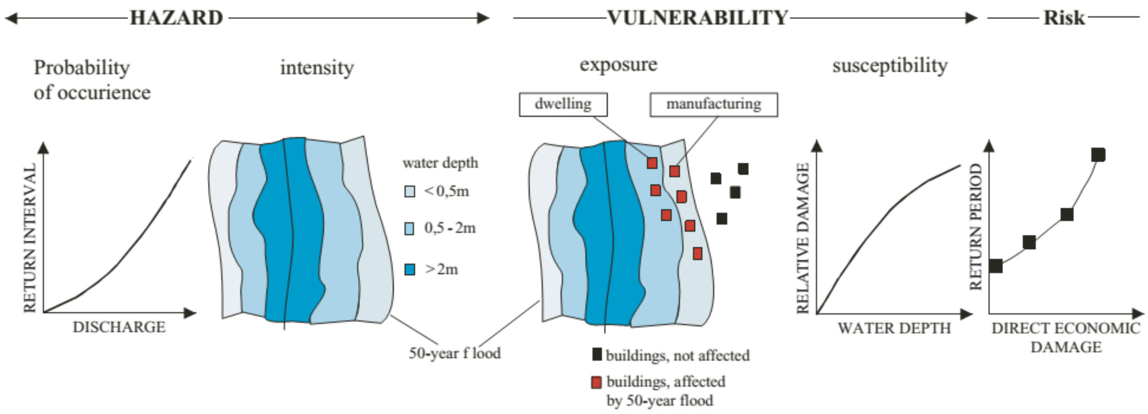


Figure 2: Flood risk as interaction of hazard (exceedance probability and intensity) and vulnerability (exposure and susceptibility)

Flood risk maps indicate potential adverse consequences associated with floods under several probabilities, expressed in terms of: the indicative number of inhabitants potentially affected; type of economic activity of the area potentially affected; installation which might cause accidental pollution in case of flooding.

1.5- Factors controlling flood hazards

Flood generation is highly a non-linear system (Maidment et al., 1999) which depends on natural and spatial/temporal variability of several factors such as: meteorological, hydrological and river (or watershed) characteristics, climatic variables, land use conditions, indices of urbanization…These following lines will discuss the factors which are classified in three different categories : factors related to the terrestrial and hydrological system, factors related to the climate system and factors related to the socio-economical system.

1.5.1- Factors related to terrestrial / hydrological system

The characteristics of terrestrial/hydrological systems play a pivotal part in driving flood risk. The most pertinent are catchment size, geology, landscape, topography and soils; the latter are often strongly modified by human intervention. Alterations in catchment surface characteristics (e.g. land cover), flood-plain storage and the river network can all modify the physical characteristics of river floods (Zbigniew W. Kundzewicz et al, 2013).

In fact, a catchment with a large area will lead to a greater flood if catchment-wide flooding occurs. Furthermore, if there is low topography, flooding will spread over a larger area. Simply, the bigger, straighter and smoother a river, creek or other channel, the greater its capacity to carry water and the less prone it is to flooding. Any process that reduces this capacity, such as the placement of structures in the channel, encroachment by development or build-up of sediment, contributes to increase in flooding. In addition, the shape of the basin also has an impact, for example steep slopes will mean water will travel downstream quickly leading to a large volume descending in to the valley floor in a short space of time (Ward and Robinson, 2000).

Moreover, river discharge is an integrated result of processes in the drainage basin—from precipitation to runoff. Land-use and land-cover changes also affect floods, as do engineering developments such as dikes and reservoirs that regulate flow processes. Structures that are placed in a creek or waterway, for example culverts in an urban drainage system or bridges in a river, reduce the water-carrying capacity of the waterway and may contribute to flooding. Debris can also become entangled on these structures, worsening this process. To add on that, levees along a waterway are designed to protect areas 'behind' the levee from floods up to a certain level, but their constraining influence on flood flows can cause upstream flood levels to be higher than they otherwise would be. Road and railway embankments, with insufficient cross-drainage capacity (for example, use of culverts), can block off parts of the floodplain with a similar effect. Once levees or embankments are overtopped or breached, the way floodwaters spread over a floodplain can alter significantly and the impact of flooding is often severe.

Besides that, a large influence on the size of a flood is how wet the soil is prior to the rainfall event occurring. If the soil is already saturated, water will not infiltrate into the ground and overland flow will occur.

Furthermore, the more vegetation there is in an area, the greater the amount of rainfall that is captured and the less water there is available to flow over the surface; consequently, the reduction of forest and wetland coverage is also reducing the role of these ecosystems in buffering flood events (Bradshaw et al. 2007; Garett, 2011). Evidence has shown that forests provide an intercepting layer for rainfall, which reduces the rate at which water reaches the surface. Forest soils also have a high organic matter which can absorb high amounts of water reducing overland flow. Plants in a river or on its banks slow the speed of the water flowing in it. The slower the water moves, the higher the water level, and the greater extent to which the floodplain surrounding the river will be inundated. This can reduce downstream flood levels and flows. Plants also reinforce river banks, decreasing erosion and increasing the deposition of sediment. In contrast, deforestation can intensify river flooding by affecting the soils structure, reducing infiltration rates and reducing water storage. (Davie, 2008, Ward and Robinson, 2000).

Additionally, increased urbanization has led to soil sealing and growth of impermeable surfaces, reducing the accommodation space for flood waters. In urban areas, the value of the runoff coefficient (portion of precipitation that enters a stream) is high, while the water-storage capacity (as in flood plains and wetlands) is low, in contrast to rural (and especially forested) areas. Processes of urbanization also lead to increased occupation of flood plains and, often, inadequate drainage planning (H12). Hence, urban and rural catchments of the same size and topography will react differently to the same amount of precipitation. The peak discharge in the urban area is usually much higher, and the time-to peak is shorter, than in the rural areas (Kundzewicz et al. 2012). These urbanization issues are universal, but often at their worst in informal settlements, where there will be no investment in drainage solutions, and flooding regularly disrupts livelihoods and undermines local food security. Flooding is also a major risk for urban areas. It is often caused by buildings, infrastructure, and paved areas that prevent infiltration and is exacerbated by overwhelmed drainage systems.

1.5.2- Factors related to the climate system

Among the principal climate-system factors that determine flood risk are the water-containing capacity (and water vapour content) of the atmosphere (Koutsoyiannis 2012) and the characteristics of intense precipitation, including its amount and distribution in space and time as affected by large-scale circulation patterns. A change in the climate could physically alter many of the factors affecting floods, for example, precipitation (volume and timing, proportions of precipitation falling as snow and rain), snow cover, antecedent soil moisture content, surface water levels, sea level, glacial lake conditions and vegetation, and thus may change the characteristics of floods (Taylor, 2014).

Precipitation is the general term for rainfall, snowfall and other forms of frozen or liquid water falling from clouds. Precipitation varies from year to year and over decades, and changes in amount, intensity, frequency, and type and affect the environment and society. The character of the precipitation when it occurs, depends greatly on temperature and the weather situation. According to Garett (2011), rainfall is the most important factor in creating a flood, because the process of flooding begins with rainfall. Floods will occur when the amount of water flowing from a catchment exceeds the capacity of its drains, creeks and rivers. The greater the rainfall intensity, the greater the potential for runoff. How long it rains, and the area covered by the rain, are also important.

In Fes city, most flood hazards were linked to the daily or instant heavy rain. In October, the 13th, 1989 for example, floods in the area were explained by the rain concentration, as it attained 37.6 mm in the Aïn Timedrine station, 40.6 mm in Sefrou and 28 mm in the Fez Saïs station. In May the 18th, 2011, several districts were flooded in Fez following the heavy rain that attained 52 mm in the city (Météorologie Nationale, 2011). However the problem appears only when flooding has an impact on human settlements and activities. The link between social, spatial and natural factors are strong as they intervene together in the flooding disasters in the area. The dominant habitat is informal because it appeared in the eighties of the last century when the expansion of spontaneous settlements had been alarming. But the increasing of the district in the same way was continuous over time due to speculation and non-respect of urbanism rules (Fejjal, 1994, Darkaoui, 2009).

Besides that, the climatic and the global change factors are also evoked among drivers of flood risks (Snoussi et al. 2008; Tramblay et al., 2012). The main predictable component of climate change in the future is that associated with human activities (IPCC, 2007). Humans are changing the composition of the atmosphere by adding carbon dioxide and visible particulates, called aerosols, mainly by burning fossil fuels. Other activities add methane and nitrous oxide, which along with carbon dioxide are greenhouse gases, so that they trap outgoing infrared radiation and warm the planet (IPCC, 2007). One consequence of increased heating from the human-induced, enhanced greenhouse effect is increasing temperature. However, another consequence is increased evaporation of surface moisture (Yu and Weller, 2007), thereby changing the hydrological cycle, provided adequate surface moisture is available (as it always is over the oceans and other wet surfaces). For precipitation for instance, climate models typically predict an increase in amount globally of 1–2% per 1°C warming in global mean temperature, although this value is quite uncertain (Allen and Ingram, 2002). A very robust finding in all climate models with global warming is for an increase in potential evapotranspiration. In the absence of precipitation, this leads to increased risk of drought, as surface drying is enhanced. It also leads to increased risk of heat waves and wildfires in association with such droughts; because once the soil moisture is depleted, all the heating goes toward raising temperatures and wilting plants. As temperatures rise, the likelihood of precipitation falling as rain rather than snow increases, especially in autumn and spring at the beginning and end of the snow season. Hence, extreme weather events such as heavy rainfall (and thus floods) are projected to become much more frequent, as the climate warms. These aspects have enormous implications for agriculture, hydrology, and water resources. For instance, On November 30, 2010, Casablanca was deluged by a record 18 centimetres of rain overnight— equal to about six months of rainfall under normal patterns. The resulting floods forced the shutdown of various facilities, including the international airport, businesses and schools throughout the city. Companies lost inventories. Streets became swirling rivers, with cars mostly submerged, and citizens struggling through waist-high water to reach places of security. More than 2,500 families had to be accommodated in various public structures. After the disaster, city councillors called for an urgent review of infrastructures, services, and institutional systems implicated in emergency response[4].

Nevertheless, it's impossible to quantify how much of the change in rainfall is caused by man and how much is due to the cyclical patterns in nature. But it is clear that a significant change is a foot: a succession of productive growing seasons with predictable sun and rain has been replaced in recent years by a series of extreme weather events. Climate change could make natural disasters more intense and more frequent. According to the Intergovernmental Panel on

[4] The World Bank, 2011

Climate Change (IPCC), North Africa, and consequently Morocco, is the world's second most vulnerable region to emerging climate-related risks. Climate events could also lead to increased internal migration and displacement which will highly influenced informal urban settlement and lead to increase in runoff and then flooding.

In general, human modifications of watersheds, changing their runoff characteristics (e.g. urbanization, deforestation, building of flood walls and dams, and artificial land drainage), lead to flood risk changes. The impacts of changes in flood characteristics will be highly dependent on how climate changes in the future, and there is low confidence in specific projections of changes in flood magnitude or frequency. However, even in the absence of increased flood risk owing to increased heavy precipitation or other modifications of the climate system, flood risk will generally increase as exposure continues to rise.

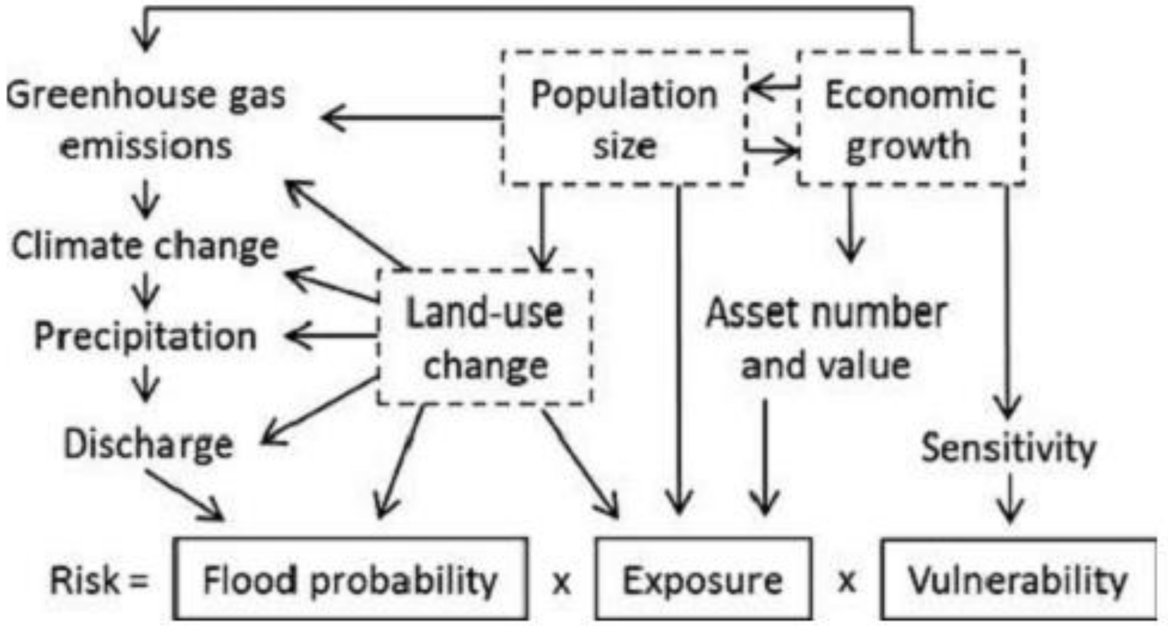


Figure 3: Anthropogenic drivers of changes in flood risk (Zbigniew et al., 2013)

1.5.3- Factors related to socio – economical system

Changes in population size and development, and level of protection, strongly influence changes in exposure to flood hazards. Over time, population has increased in most flood prone areas, and the accumulation of assets has increased exposure to loss. There are indications that exposed population and assets have increased more rapidly than overall population or economic growth (Bouwer et al. 2007, Bouwer 2011) because of increasing concentration in flood-prone areas.

- **Population growth in Fez city**

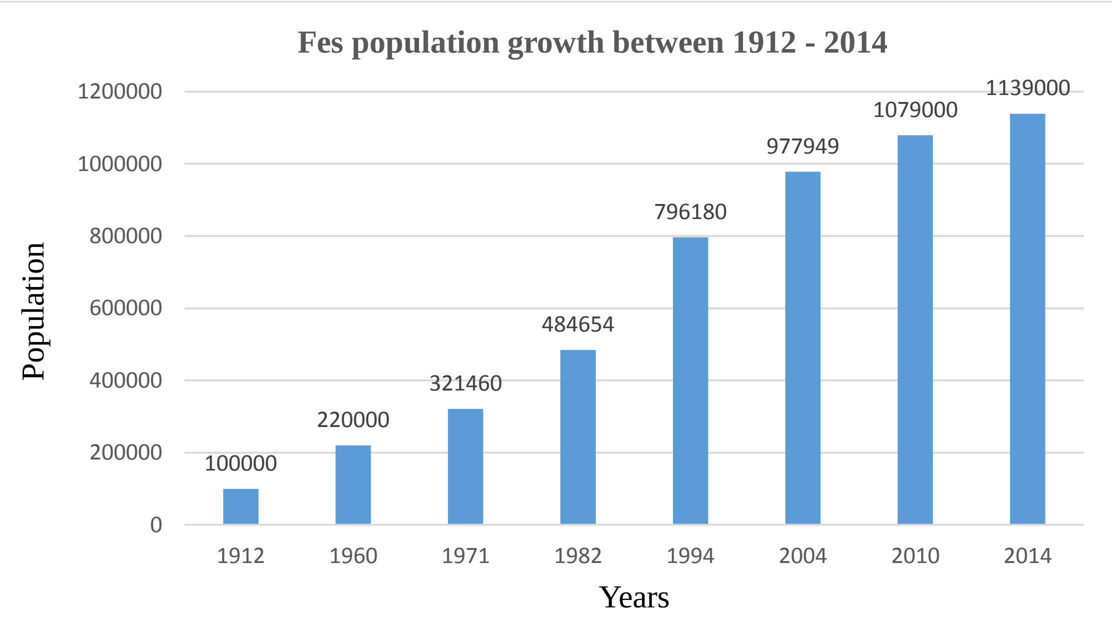
With an average annual population growth rate of about 2.1 percent, has one of the world's most rapidly expanding populations. The region is approximately 62 percent urbanized, and its urban population is expected to double over the next 3 decades. By

2030, the region will have experienced a 45 percent increase in its urban population, corresponding to over 106 million additional urban inhabitants.(World Bank, 2011)

Urbanization and the youth population will continue to increase the demand for housing and urban services, putting pressure on local authorities to expand access to urban land and provide infrastructure. Affordable housing programs and progress made to date will not be sufficient to prevent the proliferation of informal settlements. The high concentration of youth (World Bank, 2011) in urban areas is also causing informal settlements to expand.

The medina of Fes has been created since twelve centuries and constitutes today an agglomeration of 100 km2 for a population greater than one million of inhabitants. The massive rural exodus, mainly due to drought and socio-economic and political crisis; is said to be the main driver of the population growth of Fes city. As a matter of fact, its population has eleven times grown in only one century. From a hundred inhabitants in 1912, it went to more than one million one hundred thousand (Ministry of habitat and urbanism and city politic, 2013).

Owing to this demographic explosion, need in housing has dramatically increased. For instance, households in the boroughs of Zouaga and Saiss has been multiplied by two in ten years, from 1994 to 2004). In addition to that, the need in accommodation is projected to be in average of 15 000 housings in 2020; according to the Regional Observatory Service. Besides that, this need in shelter has led to building houses and settlement of people in flooding risk zones.



Graph 1: Population growth in Fez between 1912 and 2014

In addition to that, as the population was increasing, urban area is where the fastest growing population is noticed as shown in the graph below:

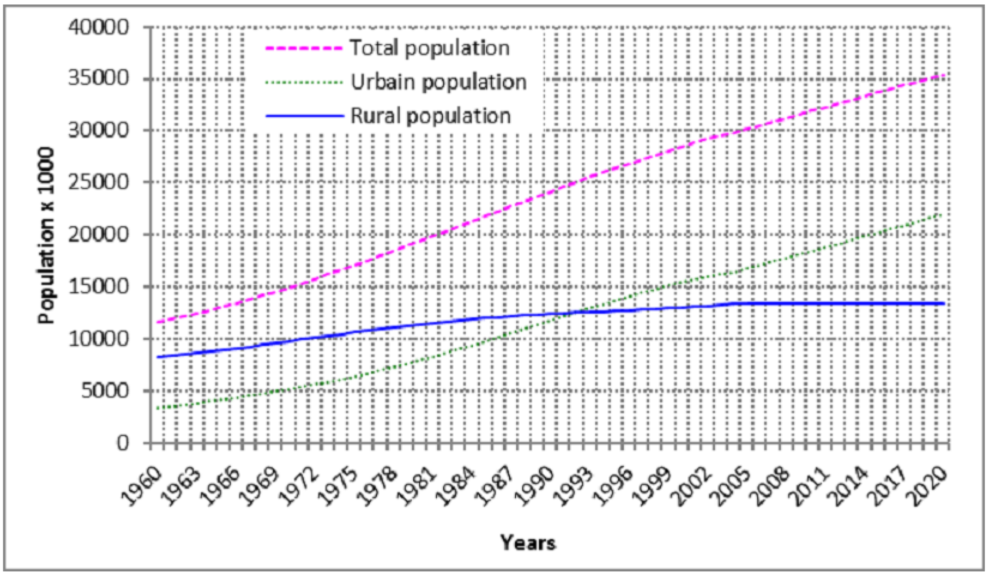
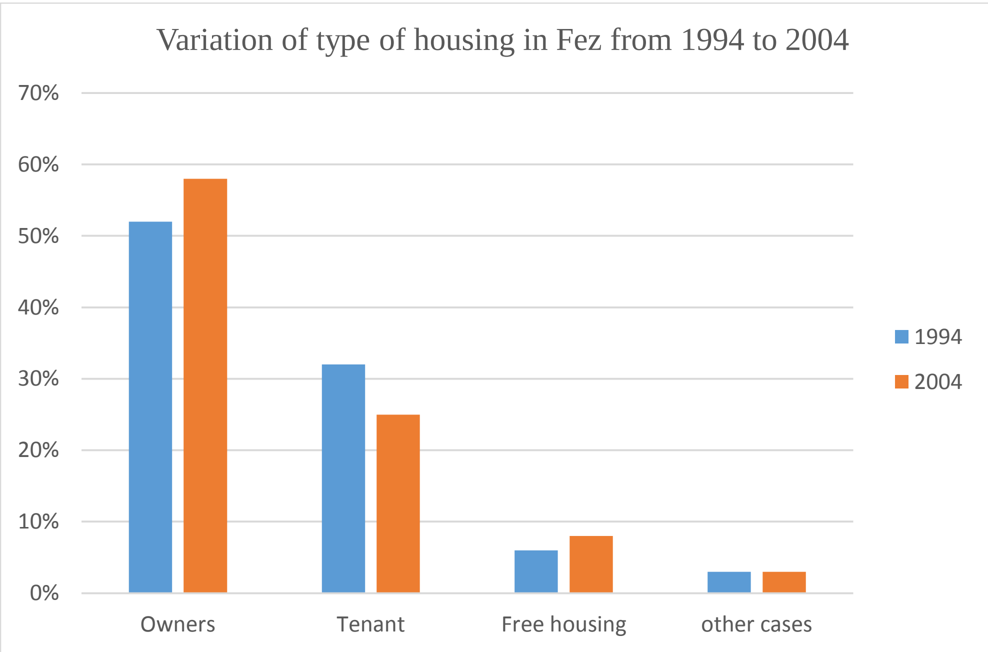


Figure 4: Population growth in urban and rural area in Morocco *(HCP 2015 in El Garouani 2016)*

Especially in Fez city, the way of housing also varied considerable due to urbanization between 1994 and 2004. Free housing increased as well as houses owners.



Graph 2: Variation of housing type in Fez from 1994 to 2004

What is more, Urbanization is a major cause of land use changes and land conversions. It makes unpredictable and long lasting changes on the landscape (El Garouani et al., 2016). The table below shows the land use change between 1984 and 2013.

Table 2: Land use change between 1984 and 2013 in Fez
Adapted from El Garouani et al. 2016

Land use	18/08/1984	18/08/2013	Change (ha)	Change (%)
Water	98	339	241	246
Urban	2041	4503	2462	121
Industrial area	116	167	51	45
Rangeland	3023	3140	117	4
Olive trees	1100	2081	981	89
Orchard	1211	1502	291	24
Forest	641	622	-19	-3
Agriculture	38761	34637	-4124	-11

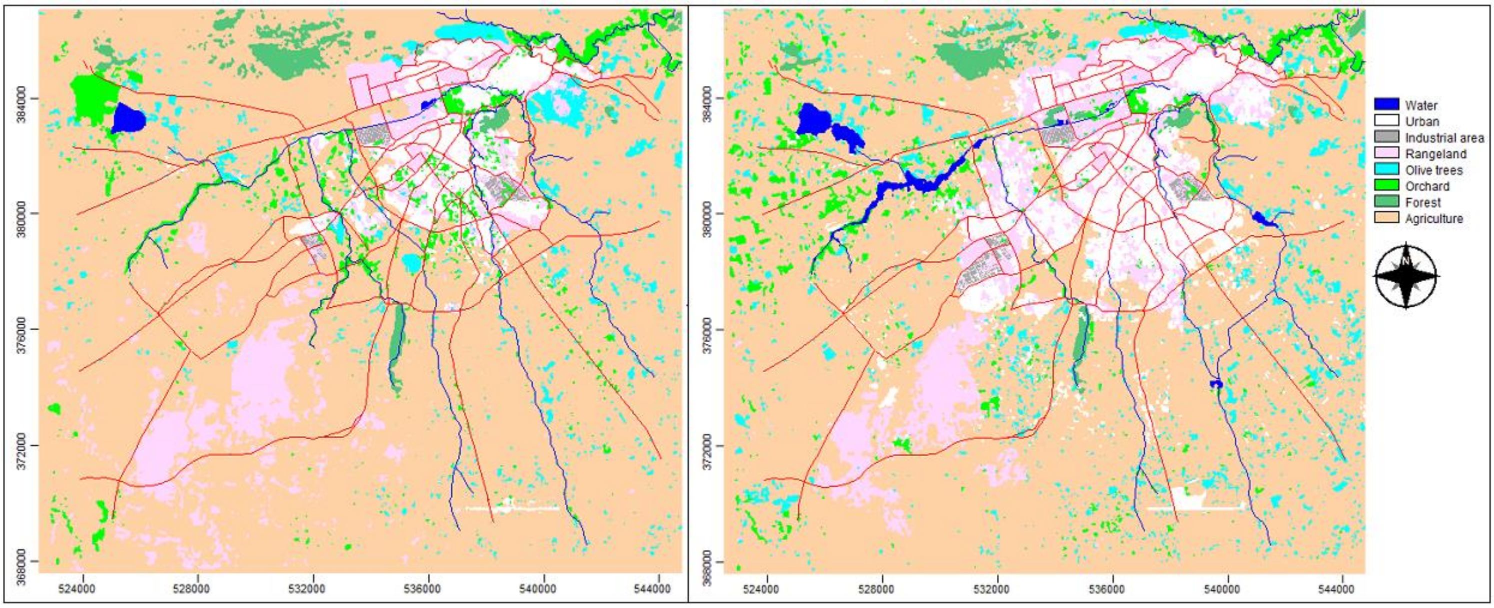


Figure 5: Land cover map of Fez *(*El Garouani et al, 2015)

1.6- Flood risk modeling and mapping

1.6.1- ArcGIS in flood risk mapping

GIS applications in flood risk mapping range from storing and managing hydrological data to generating flood inundation and hazard maps to assist flood risk management. Over the last decade in particular, a great deal of knowledge and experience has been gained in using GIS in flood risk mapping.

1.6.2- Overview of ArcGIS

Geographic Information System (GIS) is defined as an information system that is used to input, store, retrieve, manipulate, analyse and output geographically referenced data or geospatial data, in order to support decision making for planning and management of land use, natural resources, environment, transportation, urban facilities, health services.

1.6.2.1- Data input

In GIS, data collection (spatial, attribute) is split into data capture (direct data input) and data transfer (input of data from others systems) and two types of data are collected: primary data and secondary data in either raster or vector model. Spatial data specifies the location (where) and is stored in a shape file, geodatabase or a similar geographic file. Attribute data or descriptive data (what, how much, when); specifies the characteristics at that location which can be natural or human-made. It is stored in a data base table. To add on that, GIS systems traditionally maintain spatial and attribute data separately, then join them for display or analysis. Furthermore, primary data sources are those collected in digital format specifically for use in a GIS project; while secondary sources are digital and analogue datasets that were originally captured for another purpose and need to be converted into a suitable digital format for use in the GIS project.

- **Raster Data Model**

78	72	69	71	58	49
74	67	56	49	46	50
69	53	44	37	38	48
64	58	55	22	31	24
68	61	47	21	16	19
74	53	34	12	11	12

Figure 6: Raster DEM (Maidment et al, 1999)

In general terms, an image (raster) is a digital picture or representation of an object. Image data are stored in data files, also called image files, on magnetic tapes, computer disks, or other media. The data consist only of numbers. These representations form images when they are displayed on a screen or are output to hardcopy. Raster image data are laid out in a grid similar to the squares on a checkerboard. Each cell of the grid is represented by a pixel, also known as a grid cell. Raster data are obtained from aerial photography, satellite imagery, and radar, which are all forms of remotely sensed data. Usually, remotely sensed data refer to digital representation of the Earth collected from sensors on satellites or aircraft. However, there are several types of errors that can be manifested in remotely sensed data. Among these are line dropout and striping. These errors can be corrected to an extent in GIS by radiometric and geometric correction functions.

Besides that, secondary raster data are obtained using scanners: documents, film and paper maps, aerial photographs, images can be scanned and georeferenced. Georeferencing, also known as geocoding, is the geographical registration or coding of the pixels in an image. Geocoded data are images that have been rectified to a particular map projection and pixel size. Raw, remotely-sensed image data are gathered by a sensor on a platform. In this raw form, the image data are not referenced to a map projection. Rectification is the process of projecting the data onto a plane and making them conform to a map projection system.

- **Raster thematic layer**

Thematic data are raster layers that contain qualitative, categorical information about an area. A thematic layer is contained within an image file. Thematic layers lend themselves to applications in which categories or themes are used. Thematic raster layers are used to represent data measured on a nominal or ordinal scale, such as hydrology, soils, land use, land cover and roads.

- **Continuous Raster Layer**

Continuous data are raster layers that contain quantitative (measuring a characteristic on an interval or ratio scale) and related, continuous values. Continuous raster layers can be multiband (e.g., Landsat TM data) or single band (e.g., SPOT panchromatic data). Landsat, SPOT, digitized (scanned) aerial photograph, DEM, slope and temperature are some examples of types of data of continuous raster layers.

- **Vector data model**

Vector data consist of points, lines and polygons (Maidment *et al*., 1999). A point is defined by a single set of Cartesian coordinates [easting(x), northing(y)]. A line is defined by a string of points in which the beginning and end points are called nodes, and intermediate points are called vertices (Smith, 1995). A straight line consists of two nodes and no vertices whereas a curved line consists of two nodes and a varying number of vertices. Three or more lines that connect to form an enclosed area define a polygon. Ground surveying and GPS are the two main branches for vector data capture. Surveying is based on the principle that the 3-D location of any point can be determined by measuring angles and distances from other known point. It is said to be a very time consuming and expensive activity, but it is still considered as the best way to obtain highly accurate point locations. Ground surveying is typically used for capturing buildings, land and property boundaries and others objects that need to be located accurately.

Secondary vector data capture includes vectorization, photogrammetry and digitization of vector objects from maps and other geographic data sources. Vectorization is the process of converting raster data into vector data. Most of the simplest way to create vectors from raster layers is to digitize vector objects manually straight off a computer screen using a mouse or a digitizing cursor. Photogrammetry is the science and technology of making measurements from pictures, aerial photographs and images. It is a cost effective data capture technique that is sometimes the only practical method of obtaining detailed topographic data. Another type of secondary vector data capture known as coordinate geometry, is a methodology for capturing and representing geographic data. It uses survey style bearings and distances to define each part of an object.

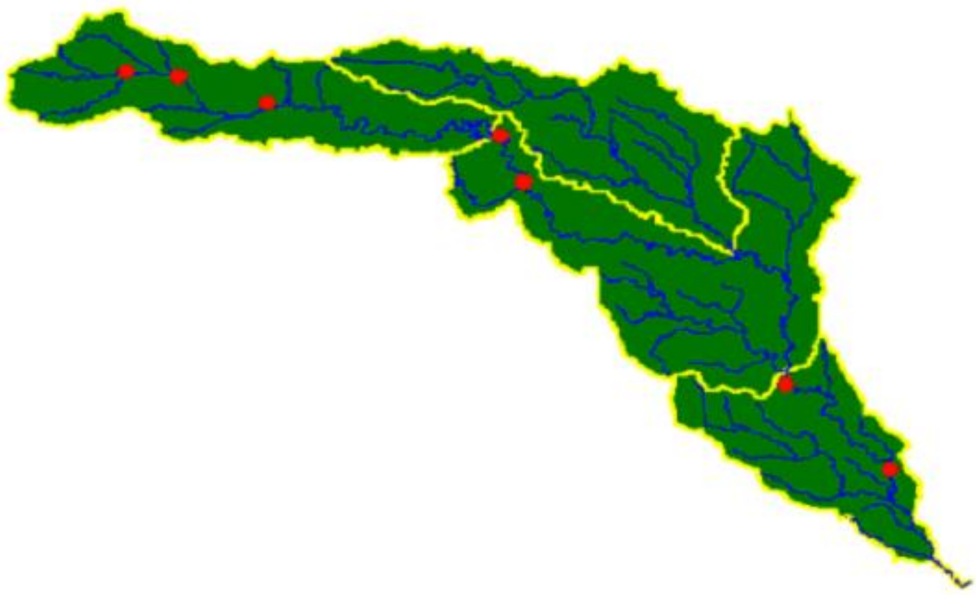


Figure 7: Vector feature representation (Maidment et al, 1999)

- **Vector data model**

The Triangulated Irregular Network model connects sample points with lines to form triangle. The triangle sides are constructed in a way that the minimum angle of each triangle is maximized. Each triangle's surface would be defined by the elevation of the three corner points. The TIN format is efficient to store data because the resolution adjusts to the parameter spatial variability. TIN triangles do not cross break lines. In three-dimensional surface representation and modeling, the TIN is generally the preferred GIS data model.

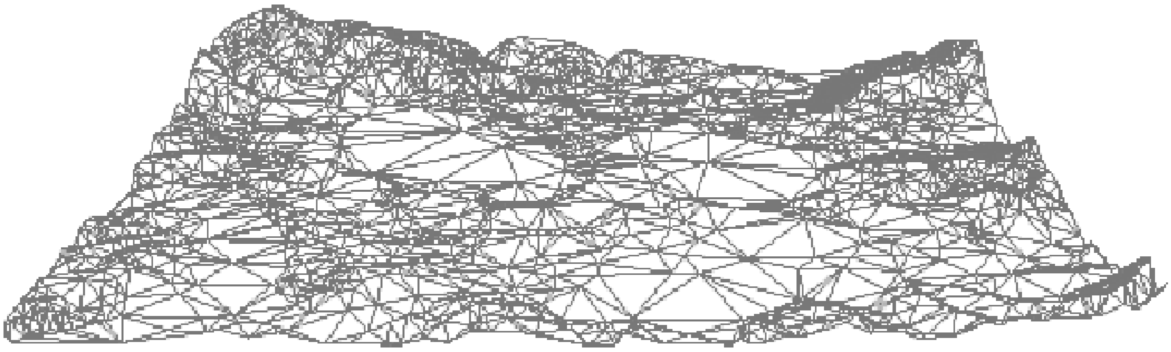


Figure 8: TIN land surface representation (Maidment et al, 1999)

With respect to this work focusing on flood risk mapping, the data normally to be gathered are cited as follow:

- **Topographic data**

Topography, according to ASCE (1999), plays an important role in the distribution and flux of water and energy within the natural landscape. Classical example will include surface runoff, evaporation, Infiltration, which are hydrologic processes whose quantitative assessment depends on the topographic configuration of the landscape. The main sources of information are from topographic maps, aerial photography, and satellite imagery. Satellite imagery is a viable alternative if up-to-date topographic maps are not available. Nowadays, Google Earth provides excellent imagery for almost all corners of the world in good to very good resolution 21. Landscape topography is an important input requirement for flood assessment and mapping. It can be digitized into an array of elevation values called Digital Elevation Model (DEM). Landscapes topography features such as slope, aspect, flow, length, contributing areas, and drainage divides; can rapidly and reliably be determined from DEM.

- **Surface elevation**

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

- Land use and cover
    - Wooden vegetation and biotopes
    - Bathymetry of the watershed
- Hydrologic data
    - Rainfall and discharges measurements
    - Runoff data

    - Flood seasons
    - Watershed morphology
    - Return flood periods
    - Hydrologic data are relevant to estimate peak discharge, for the construction of hydrographs or for the estimation of discharge-frequency relations.

- Hydraulic data: hydraulic data describe the discharge conditions in and around the channel. Three spatial sections and the respective roughness are relevant: flood plain – river bank – riverbed (cross section)
    - Stage discharge relationship at the downstream end of the river section
    - Historic flood records: delineation line of flood, velocities, water surface elevation, duration of water levels, levels of danger
    - Hydrograph of water stage and/or discharge; including peak discharge
    - Roughness parameter: A reliable evaluation of the roughness parameters needs good experience. Aerial images, land use maps and biotope distribution maps can be used for a fist classification of roughness zones but results require thorough field check. The best basis to evaluate the roughness in the river bed would be through taking bed material samples at various locations of the aquatic zone and determining the grain size distribution curve in the laboratory. But often only visual control of the bed material is possible. An intermediate solution is the "transect-by-number" sample of the armour layer.

- Demographic and socio economic conditions: Social and socio-economic data are used for the assessment of exposure and vulnerability and finally for the assessment of risks in a given location.
- Existing infrastructure
- Information on the damages caused by previous flood disasters

1.6.3- GIS support for flood risk mapping

The integration capabilities of satellite data with GIS have opened up opportunities for quantitative analysis of hydrological events, such as flood, at all geographic and spatial scales (10). For the last two decades advancement in the field of remote sensing and geographic information system (GIS) has greatly facilitated the operation of flood mapping and flood risk assessment. (Coppock, 1995). The main advantage of using GIS for flood management is that it not only generates a visualization of flooding but also creates potential to further analyse this product to estimate probable damage due to flood (Hausmann *et al.*, 1998; Clark, 1998).

Integration of hydraulics models and GIS have been improved in recent years to facilitate the manipulation of models output. Mcdonnell (1996), Pullar and Springer (2000) identified three (3) possible ways of system integration as: loose coupling, tight coupling and fully integrated. Loose coupling integrates GIS systems and hydraulic models with common file exchange, usually in ASCII format. However, tight coupling which can be defined as a system that provides a graphic user interface (GUI) for viewing and controlling the application that may also link to different subroutines or components programs; shows a more remarkable trend in system design, input and output control (Pullar and Springer, 2000). Besides that, the fully integrated requires a model to be programmed and act as a component of the GIS core program using programing languages such as Avenue Script in ArcView GIS and Arc Macro language in ArcInfo.

Geographical Information System has been widely used for flood modelling where it is integrated or coupled with models. For instance, Robayo et al. (2004) developed a new Map-to-Map tool that couples NEXRAD precipitation time series with GIS applications and hydrological modeling to produce a floodplain map. This Map-to-Map technology involves the creation of an ArcHydro data model in GIS, an Interface Data Model (IDM) for each outside model that shares data with the GIS, and a number of scripts to process the data in GIS (see Whiteaker et al. (in review) and Whiteaker and Maidment 2004 for more details.). In addition, Chen et al. (2009) developed a GIS-based urban flood inundation model GUFIM, which consists of two components: a storm–runoff model and an inundation model. The model has been applied to the main campus of the University of Memphis which has suffered repeatedly from flash flood events over several years, where frequent heavy rains overwhelm the capacity of underground sewer systems (see NOAA, 1996, 1997, 1998, 1999, 2001 ; University of Memphis, 2006, Chen et al., 2009). GUFIM is said to be an alternative to physical-based dynamic models characterized by accurate results, efficient performance, and reasonable input and hardware requirements.

1.7- Review of flood risk model

Modelling approach to develop flood risk mapping involves hydrological and hydraulic models, which are applied to simulate floods of a particular magnitude occurring in a channel/channel system. These models address the estimation of design floods (flood hydrograph) as well as the flooding process (hydraulic modelling). They have been the development of different types of models such as deterministic or random models, lumped, semi distributed and fully distributed. Other categories include black boxes, physically based models. Another type of classification for hydraulic models include one, two or three dimensional models (1-D, 2D, or 3-D)

1.7.1- Lumped models

Parameters do not vary spatially within the basin & response is evaluated only at the outlet, without explicitly accounting for the response of individual sub basins. Some examples are SCS-CN based models; IHACRES, WATBAL.

1.7.2 Semi – distributed models

The parameters of the semi distributed models are partially allowed to vary in space by dividing the basin into a number of smaller sub basins. In other words, distributed models are a set of algorithms that generates input required for hydrologic/hydraulic modelling by considering subunits of the water shed under study (ASCE 1999, Eldho 2000). There are mainly two types: Kinematic wave theory models (HEC-HMS model) and simplified version of surface flow equations of physically based model. One advantage is that the structure is more physically based than the lumped models and they require less data input than distributed models. SWMM, HEC-HMS, TOPMODEL, SWAT are some examples of semi distributed models.

1.7.3- Distributed models

These types of models, for instance HYDROTEL, MIKE11/SHE, WATFLOOD, MARINE; require a large amount of data; and their parameters are fully allowed to vary in space at a resolution chosen by the user. Governing physical processes are model in detail. Distributed models are said to provide highest accuracy in the rainfall runoff modelling but if accurate data is available.

1.7.4- One Dimensional (1-D)

1D models are simplified models that characterize the terrain using a series of cross sections. At each cross section, the flow depth and velocity perpendicular to the cross section is computed (Wright, 2015). These models are well suited for areas where the direction of flow is well defined. The best-known 1D model is HEC-RAS from the U.S. Army Corps of Engineers.

1.7.5- Two Dimensional (2-D) and (3-D)

Wright (2015) mentioned that 2D models calculate the flow both parallel and non-parallel to the main flow. They are useful for modeling areas of complex topography such as wider floodplains or broad estuaries but require high quality data and can require long computation times. Examples of 2D models include TELEMAC 2D, SOBEK 1D2D, and Flo2D. Because of their greater sophistication, most 2D models are not freely available. In addition, some models, such as LISFLOOD-FP, are called quasi-2D, and combine some of the benefits of 2D models with some of the simplicities of 1D models. The use of 3D models such as Delft3D is increasingly common, particularly for simulating coastal flooding due to storm surge.

1.8- Description of some models

1.8.1- SCS-CN

The original SCS-CN method was designed to predict direct (surface) runoff, as an infiltration-excess overland flow model. It assumes that only one process is responsible for producing streamflow over the entire watershed area. The SCS-CN supports Horton’s overland flow mechanism to compute the surface runoff (Geetha et al, 2007). It was first developed by the United States Department of Agriculture (USDA) in 1954 to transform rainfall to direct surface runoff. It has been widely used in numerous models, (Heaney et al. 2001) for single events;

long term hydrological impact assessment model, L-THIA (Harbor 1994; Bhaduri 1998); SWAT model (Spruill et al. 2000); CELTHYM (Choi et al. 2002) etc.

In addition to the application of the SCS-CN model in long-term simulation (Huber et al. 1976; Williams and LaSeur 1976; Knisel 1980; Soni and Mishra 1985; Woodward and Gbuerek 1992; Mishra et al. 1998; Mishra and Singh 1999, 2004a; Mishra 2000), this method has also been employed for determination of infiltration and runoff rates (Mishra 1998; Mishra and Singh 2002a,b, 2004b).

Besides that, the SCS-CN model was extended to estimate sediment yield and to model soil moisture (Reshmidevi et al., 2008; Singh et al., 2008). Some researchers also integrated the SCS-CN model into the GIS/RS system to extend the model applicability to complex watersheds with high temporal and spatial variability in soil and land use (Zhan and Huang, 2004; Geetha et al., 2007). The theory underlying the SCS-CN model is that runoff can be related to soil-cover complexes and rainfall through a curve number. The model assumes that the ratio of actual soil retention after runoff begins to potential maximum retention is equal to the ratio of direct runoff to available rainfall. This relationship, after algebraic manipulation and inclusion of simplifying assumptions, results in the following equation (USDA SCS, 1985):

$$\boldsymbol{Q/(P - Ia) = F/S}$$

Where,

$Q = runoff\ (mm),$

$P = storm\ rainfall\ (mm),$

$Ia = initial\ abstarction,$

$F = cumulative\ infiltration$

$S = potential\ maximum\ retention\ or\ infiltration\ (mmm)$

1.8.2- WatBal

WatBal (Water balance model for climate impact analysis), is an integrated water balance model developed for assessing the impact of climate change on river basin runoff. The conception of the model was originally developed by Z. Kaczmarek. Kaczmarek Z. in 1993. After that, Yates (1994) implemented the model through Microsoft Excel 5.0 worksheet with some dataset including monthly averages of air temperature (°C), relative air humidity (%), sunshine duration (hours), wind speed (m/s), precipitation (mm) and runoff (m 3/s). WATBAL is in the tradition of the water balance calculations developed by Thornthwaite (Thornthwaite and Mather 1957, Xu and Singh 1998). It is also such a soil water balance model that can help to estimate the monthly soil water flux values within the rooting zone. Mike Starr at the University of Helsinki, Finland in 1999, developed the model but it was not adequately tested and verified in the past It is an end-of the-month book keeping of the monthly precipitation inflow, evapotranspiration and drainage (soil water flux) outflows, and changes in soil water storage: P = ET + R ± DSM where: P= precipitation, ET= evapotranspiration, R= runoff (soil water flux), and ± DSM = changes in soil moisture storage. All units are in mm of water per month. The model is based on a series of algebraic equations, many of which are conditional to ensure rational results.

1.8.3- SWMM

The USEPA Storm Water Management Model (SWMM) is a computer program that computes dynamic rainfall-runoff for single event and long-term (continuous or period-of-record) runoff quantity and quality from developed urban and undeveloped or rural areas. The runoff component of SWMM operates on a collection of sub catchment areas that receive precipitation and generate runoff and pollutant loads. The routing portion of SWMM transports this runoff overland and underground through a system of pipes, channels, storage and treatment devices, pumps, and regulators. SWMM tracks the quantity and quality of runoff generated within each sub catchment, and the flow rate, flow depth, and quality of water in each pipe and channel during a simulation period comprised of multiple time steps. SWMM was first developed in 19711 and has undergone several major upgrades since then. It continues to be widely used throughout the world for planning, analysis, design, management and litigation related to storm water runoff, combined sewers, sanitary sewers, and other drainage systems in urban areas, with many applications in non-urban areas as well. SWMM accounts for various hydrologic processes that produce runoff from urban areas. These include: time-varying rainfall; evaporation of standing surface water; snow accumulation and melting; rainfall interception in depression storage; infiltration of rainfall into unsaturated soil layers; percolation of infiltrated water into groundwater layers; interflow between groundwater and the drainage system; nonlinear reservoir routing of overland flow; and capture and retention of rainfall/runoff with various types of low impact development (LID) practices. Spatial variability in all of these processes is achieved by dividing a study area into a collection of smaller, homogeneous (to the extent that their processes can be reasonably represented by parameters averaged over the sub-area) sub catchment areas, each containing its own fraction (or not) of pervious and impervious sub-areas. SWMM also contains flexible hydraulic modeling capabilities to route runoff and external inflows through the drainage system network of surfaces, pipes, channels, storage/treatment units and diversion structures. These include the ability to: handle networks of unlimited size; use a wide variety of standard closed and open conduit shapes as well as natural channels; model special elements such as storage/treatment units, flow dividers, pumps, weirs, and orifices; apply external flows and water quality inputs from surface runoff, groundwater interflow, rainfall-dependent infiltration/inflow, dry weather sanitary flow, and user-defined inflows; utilize steady-state, kinematic wave or full dynamic wave flow routing methods; model various flow regimes, such as free-surface, backwater, surcharging, reverse flow, surface ponding and surface flooding; apply rating curves for inlet controls; and apply user-defined dynamic control rules to simulate the operation of pumps, orifice openings, and weir crest levels.

1.8.4- TOPMODEL

TOPMODEL is a rainfall-runoff model (Beven and Kirkby, 1979) that takes advantage of topographic information (specific catchment area and wetness index) related to runoff generation, although Beven et al. (1995) prefer to consider TOPMODEL as not a hydrological modeling package, but rather a set of conceptual tools that can be used to reproduce the hydrological behavior (in particular the dynamics of surface or subsurface contributing areas) of catchments in a distributed or semi-distributed way (see Beven et al., 1995 for more details). The model uses four basic assumptions to relate down slope flow from a point to discharge at the catchment outlet:

- The dynamics of the saturated zone are approximated by successive steady state representations;
- The recharge rate r [m/hr] entering the water table is spatially homogeneous.
- The effective hydraulic gradient of the saturated zone is approximated by the local topographic surface gradient S (tanβ is the notation most common in TOPMODEL descriptions).
- The effective down slope transmissivity T of a soil profile at a point is a function of the soil moisture deficit at that point. This is commonly based on an exponential decrease of hydraulic conductivity with depth, but Ambroise et al. (1996) generalized this to also include linear and parabolic relationships. (Tarboton, 2003)

1.8.4- Hydrotel

The HYDROTEL hydrological model has been developed to simulate stream flow either within an operational forecasting framework or study framework. It is a spatially distributed hydrological model with physical bases specifically developed to facilitate the use of remote sensing and geographical information system data (website).It is used for the estimation of probable maximum floods from rain and/or snowmelt; in addition to the estimation of hydrological effects resulting from changes in the physical characteristics of a basin; and the real time forecast of river flows using meteorological forecasts. In HYDROTEL, most simulations algorithms are based on physical processes and the choice of algorithms allow a better use of all available data. Moreover, HYDROTEL facilitates the addition of new algorithms or modules. The model can be applied to a large number of basins and its simulation time steps can vary from 1 to 24 hours.

1.8.5- WATFLOOD

WATFLOOD is a distributed model used for one-way linking with atmospheric models. WATFLOOD and WATCLASS take the grid data, initial conditions and input data and execute a series of internal calculations representing the physical processes of the water cycle. The physical processes are represented by mathematical equations. The result is a distributed representation of output data that can be evaluated against using other data sets. Both WATFLOOD and WATCLASS use a Grouped Response Unit (GRU) approach in calculating the overland flow, interflow and Baseflow, collectively known as the runoff response. Using remotely sensed land cover data, pixels are classified to a number of land cover classes and the ratio of each land cover in each computation grid is determined. The runoff response from each hydrologically significant sub-group in each grid is calculated and routed downstream. With this method, there is no requirement for grids or sub-basins to be hydrologically homogeneous. So, the grid size can be chosen to conveniently match the resolution of the meteorological data or reflect the detail required in the model output.

1.8.6- MARINE

MARINE (Model of Anticipation of Runoff and INundations for Extreme events), is a distributed hydrological physically based model for flash floods forecast. Its general flow-chart is presented on Figure n°9 and detailed by Estupina-Borrell (2004) and Estupina-Borrell et al. (2005). MARINE was formulated to make flash floods prediction caused by surface runoff process. In front of the rareness, violence and rapidity of flash floods, MARINE had to find its necessary data for calibration outside the classical measurements and observations. The model consists in two steps, or two components. The first component is a “basin” flood module which generates flood runoff in the upstream part of the watershed, and the second component is the “stream network” module, which propagates the flood in the main river and its subsidiaries. The minimum data required by the model are: the Digital Elevation Model, used to calculate slopes that generate runoff, the rainfall data and the spatially distributed soil and other surface properties (land cover map, main rivers…), river morphology, topography and roughness. MARINE has been tested for the flash flood of the Orbieu river basin (Lagrasse village, southern France) on the 12 and 13 of November 1999. The main advantages of MARINE are its ability to run on insufficiently gauged basins (with the help of satellite information) and to run in an operational mode for real-time flood forecasting. However, MARINE is a physically-based distributed hydrological model, which demands for more sophisticated data. Another issue with the model is related to its calibration (or data assimilation) of with respect to the initial saturation state of the basin

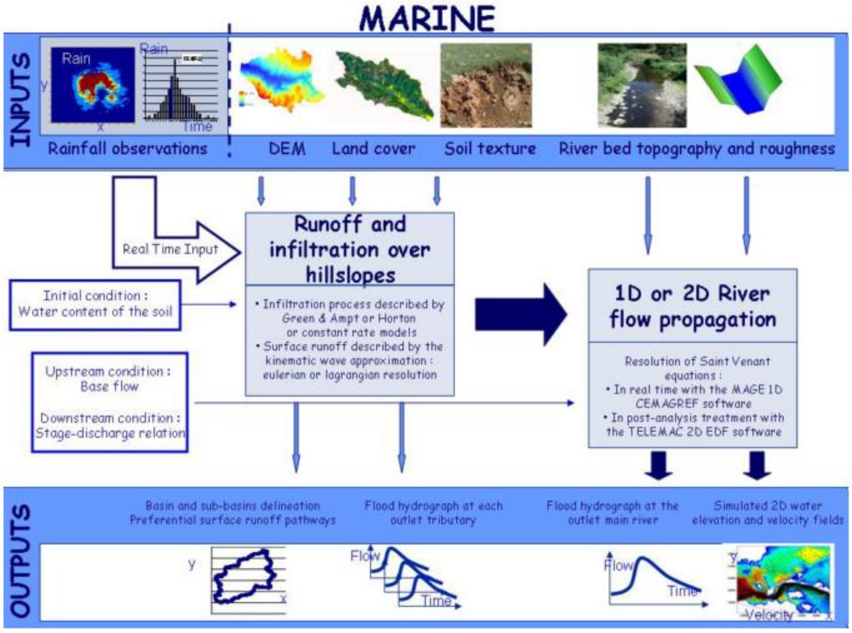


Figure 9: Marine flow chart

1.8.7- MIKE11/SHE

Since the mid-1980's, MIKE SHE has been further developed and extended by DHI Water & Environment. It was developed as a fully integrated alternative to the more traditional lumped, conceptual rainfall-runoff models (DHI, 2000). MIKE SHE covers the major processes in the hydrologic cycle and includes process models for evapotranspiration, overland flow, unsaturated flow, groundwater flow, and channel flow and their interactions. Each of these processes can be represented at different levels of spatial distribution and complexity, according to the goals of the modeling study, the availability of field data and the modeler's choices, (Butts et al. 2004). MIKE SHE uses MIKE 11 (Havnø et al. 1995) to simulate channel flow. MIKE 11 includes comprehensive facilities for modelling complex channel networks, lakes and reservoirs, and river structures, such as gates, sluices, and weirs. It provides a library of computational methods for steady and unsteady flow in branched and looped channel networks as well as quasi two-dimensional flow simulation flood plains. MIKE 11 also includes simple hydrologic routing methods, which are suitable when the detailed flow dynamics in the river are not of interest. Besides that, MIKE 11 GIS has been developed to connect the 1D MIKE 11 hydraulic model and ArcView GIS; where floodplain topography can be extracted from a DEM and imported into MIKE 11. After running the model, MIKE 11 GIS can prepare three types of floodplain maps for display and analysis in ArcView: depth/area inundation, duration, and comparison/impact (DHI, 1999). To add on that, MIKE 11 GIS can produce output graphs of water level time series data, terrain and water level profiles, and flood zone statistics.

There are, however, important limitations to the applicability of such physics based models. For instance, it is widely recognized that such models require a significant amount of data and the cost of data acquisition may be high; the relative complexity of the physics-based solution requires substantial execution time.

1.8.8- SMS

SMS, Surface water Modelling System, is a graphical user interface designed to serve as pre and post processor for hydraulic modelling of river channels. It has been developed by the Environmental Modelling Research Laboratory and it can be used to extract stream cross-sections from a TIN surface. For two dimensional modelling, SMS is used to develop finite element meshes.

1.8.9- SWAT

The Soil and Water Assessment Tool (SWAT) is a physical process based model to simulate continuous-time landscape processes at a catchment scale (Arnold et al., 1998; Neitsch et al., 2005). The catchment is divided into hydrological response units (HRUs) based on soil type, land use and slope classes that allows a high level of spatial detail simulation. The major model components include hydrology, weather, soil erosion, nutrients, soil temperature, crop growth, pesticides agricultural management and stream routing. The model predicts the hydrology at each HRU using the water balance equation, which includes daily precipitation, runoff, evapotranspiration, and percolation and return flow components. The surface runoff is estimated in the model using two options (i) the Natural Resources Conservation Service

Curve Number (CN) method (USDA-SCS, 1972) and (ii) the Green and Ampt method (Green and Ampt, 1911). The percolation through each soil layer is predicted using storage routing techniques combined with crack-flow model (Arnold et al., 1995). The evapotranspiration is estimated in SWAT using three options (i) Priestley-Taylor (Priestley and Taylor, 1972), (ii) Penman-Monteith (Monteith, 1965) and (iii) Hargreaves (Hargreaves and Riley, 1985). The flow routing in the river channels is computed using the variable storage coefficient method (Williams, 1969), or Muskingum method (Chow, 1959). The SWAT model uses the Modified Universal Soil Loss.

1.8.10- IHACRES

The IHACRES model is a hybrid conceptual-metric model, using the simplicity of the metric model to reduce the parameter uncertainty inherent in hydrological models while at the same time attempting to represent more detail of the internal processes than is typical for a metric model. Figure n°10 shows the generic structure of the IHACRES model. It contains a non-linear loss module which converts rainfall into effective rainfall (that portion which eventually reaches the stream prediction point) and a linear module which transfers effective rainfall to stream discharge. Further modules can be added including one that allows recharge to be output. The inclusion of a range of non-linear loss modules within IHACRES increases its flexibility in being used to access the effects of climate and land use change. The linear module routes effective rainfall to stream through any configuration of stores in parallel and/or in series. The configuration of stores is identified from the time series of rainfall and discharge but is typically either one store only, representing ephemeral streams, or two in parallel, allowing base flow or slow flow to be represented as well as quick flow. Only rarely does a more complex configuration than this improve the fit to discharge measurements (Jakeman and Hornberger, 1993).

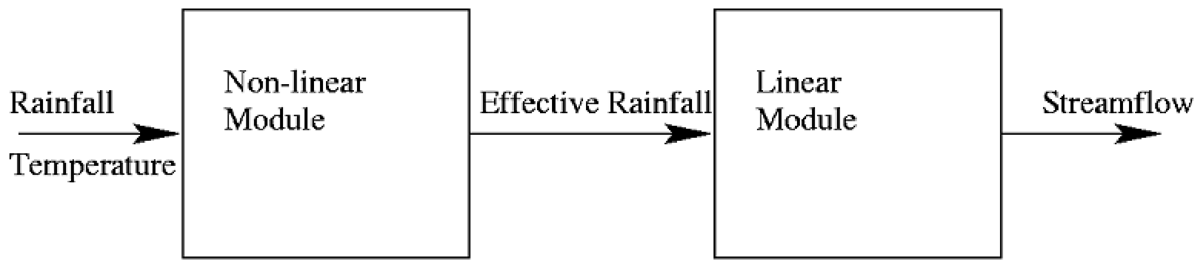


Figure 10: Generic structure of IHACRES model (Jakeman and Hornberger, 1993)

The figure is showing the conversion of climate time series data to effective rainfall using the Non-linear Module and the Linear Module converting effective rainfall to stream flow time series.

1.8.11- TUFLOW

TUFLOW is a suite of advanced numerical engines and supporting tools for simulating free-surface water flow for urban waterways, rivers, floodplains, estuaries and coastlines. The software was used to simulate flood extent, depth and velocity. The TUFLOW engines are technically able in solving all the necessary physical processes using 1D, 2D and 3D solutions. The system uses third party Graphical User Interfaces (GUI) and Geographic Information Systems (GIS) to provide the modelling environments. At the core of TUFLOW, are three numerical engines known as (i)TUFLOW 2D grid based and linked 1D network solver; (ii) TUFLOW GPU, a 2D only grid based solver using the parallel processing power of the modern GPU for fast simulations; and (iii)TUFLOW FV, a 2D/3D flexible mesh finite volume solution.

1.8.12- HEC-HMS

The model package HMS (define) is designed to simulate the precipitation-runoff processes of dendritic watershed systems. It is designed to be applicable in a wide range of geographic areas for solving the widest possible range of problems. This includes large river basin water supply and flood hydrology, and small urban or natural watershed runoff. In addition, it allows calibrating a few different models including, at the event based level: Clark's model, Snyder's model, SCS-UH model and Kinematic wave model.

This simplified representation of the runoff process does not account for the storage and movement of water vertically within the soil layer. It is however sufficient to model a flood hydrograph as the result of a storm (HEC, 2000). For modelling purposes, this simplified hydrologic cycle is further divided into four components, which are modelled separately. The models included in the software can thus be categorized as follows:

Loss Method: A model to compute the runoff volume is often referred to as the loss method since it accounts for the losses that occur during a rainfall event as a result of infiltration and evapotranspiration. For each time interval in the modelling process, the loss method calculates the amount of water that contributes to the runoff in the river (effective rainfall).

Transform Method: Models of direct runoff are also called transform method, since they convert the effective rainfall over a watershed into a hydrograph at the outlet of the watershed. These models account for the surface roughness and geometry of the watershed.

Baseflow Method: Baseflow models are used to simulate the fraction of the runoff contributed by groundwater.

Routing Method: If the analysed watershed is divided into sub-watersheds, the flow at the outlet of a certain upstream watershed has to be routed through the river channel in the downstream watershed. The models used to simulate this routing process are therefore called routing methods. They account for the geometry and roughness of the relevant river channel.

HEC-HMS comes with an Arc-View extension (HEC-GeoHMS) which automates the construction of the model input and especially the averaging of soil type and land cover properties, topography and local drainage delineation, through the full exploitation of GIS hydrographic delineation capabilities. HEC-GeoHMS creates background map files, basin model files and a grid cell parameter file which can be used by HEC-HMS to develop a hydrologic model. The basin model file contains hydrologic elements and their hydrologic connectivity. The basin model file includes sub basins areas and other hydrologic parameters that could be estimated using geospatial data. To assist with estimating hydrologic parameters, HEC-GeoHMS can generate tables containing physical characteristics of streams and watersheds.

1.8.13- HEC – RAS

1.8.13.1- General overview

In 1964, HEC released the HEC-2 computer model to aid hydraulic engineers in stream channel analysis and floodplain determination. HEC-2 quickly became the standard stream hydraulic analysis program, and its capabilities were expanded in the ensuing years to provide for, among other things, bridge, weir, and culvert analyses. (Beavers, 1994 ; Maidment et al, 1999)

Due to the increased use of Windows-based personal computing software in the early 1990's (Maidment et *al, 1999),* HEC released a Windows-compatible counterpart to HEC-2 called the River Analysis System (RAS). HEC-RAS has a graphical user interface programmed in Visual Basic, to which are attached flow computation algorithms programmed in FORTRAN, many of which were derived from the HEC-2 model. HEC-RAS is a hydraulic modeling software developed by the United States Army Corps of Engineer´s Hydrologic Engineering Center. In this study, version 4.1.0 of HEC-RAS

HEC-RAS is an integrated system of software, designed for interactive use in a multi-user network environment. The system is comprised of a geographical user interface (GUI), separate hydraulic analysis components, data storage and management capabilities, graphics and reporting facilities.

The HEC-RAS system contains four one dimensional river analysis components for (i) steady flow water surface profile computations, (ii) unsteady flow simulation, (iii) movable boundary sediment transport computations and (iv) water quality analysis. A key element is that all the four components use a common geometric data representation and common geometric and hydraulic computation routines. In addition to the four river analysis components, the system contains several hydraulic design features that can be invoked once the basic water surface profiles are computed.

The HEC-RAS Technical Reference Manual (HEC, 2010b) is a detailed and complete documentation of the model and the underlying equations; nevertheless, the basics concepts of one dimensional flow routine are explained in the following lines.

1.8.13.2- Basic concepts of one dimensional flow routing

In hydraulics, the flow of water in a river is referred to as open channel. Open channel flow is defined as the flow of a free surface fluid within a defined channel. Typical examples are flow in natural streams, constructed drainage canals, and storm sewers. This type of flow can be classified based on time, space and flow regime. Therefore, with respect to time, open channel flow can either be steady or unsteady, where respectively; depth and velocity at a specific location do not change or change with time. 1 -D models are subdivided into steady and unsteady-flow models. According to space classification, the term uniform is used to denote fluid flow in which depth and velocity are constant with distance (conditions require the channel to be straight, with constant cross-sectional geometry, and a water surface that is parallel to the base of the channel); whereas non-uniform or varied flow is used when the water depth and velocity change with distance along the channel. Concerning the flow regime, the Froude number is used to classify the flow type. The flow can either be subcritical, critical or supercritical. This distinction between subcritical and supercritical flow is important to consider for the modelling of open channel one dimensional flow. In fact, for a fixed discharge, there is a critical flow depth, for which the specific energy of the flow is at its minimum. If the specific energy is not at its minimum for a fixed discharge, the flow depth can either be higher than the critical depth (subcritical); or lower (supercritical). Situations in which both flow types occur in the modelled reach are referred to as a mixed-flow regimes. HEC-RAS is currently capable of performing one dimensional water surface profiles calculation for steady, gradually varied flow in natural or constructed open channel. Subcritical, supercritical and mixed flow regime water surface profiles can be calculated.

Moreover, in one-dimensional flow routing, flow through the river channel and the floodplains is treated only in the longitudinal direction parallel to the conduit. Even though in reality, the flow in a natural channel is never truly 1-D, these flow models were found to deliver acceptable results for predicted hydraulic parameters in many applications (Arizona Department of Water Resources, 2002).

Besides that, in inundation analysis, flow models simulate the flow through the open channel in a way that satisfies the continuity of mass, the continuity of energy and the continuity of momentum.

1.8.13.3- Data requirements in HEC-RAS

To compute water surface elevation at any location of interest, for either a given set of flow data (steady flow simulation) or by routing hydrograph through the system (unsteady flow simulation); the data needed are divided in geometric data, steady flow data and unsteady flow data. Geometric data are required for any analysis within the HEC-RAS environment.

The connectivity between the River System Schematic, the cross section data, the reach lengths, the energy loss coefficients and the stream junction information is the basic geometric data required, in addition to the hydraulic structure data ‘bridges, culverts, spillways, weirs, etc.).

Steady flow data consist of flow regime, boundary conditions and peak discharge information. The flow regime (subcritical, supercritical or mixed flow regime) is specified on the steady flow analysis window of the user interface. Furthermore, boundary conditions are essential to precise the upstream and downstream of the river system. Boundary conditions are only needed at the downstream end of the river for a subcritical flow regime while they are only necessary at the upstream ends of the river if a supercritical flow is going to be computed. For a mixed flow regime computation, the conditions have to be entered at all ends of the river system. There are four types of boundary conditions described in the reference manual, known as: water surface elevation, critical depth, normal depth and rating curve. As far as discharge data is concerned, it is required at each cross sections of the system and must be entered for the total number of profiles that are to be computed. Discharge information from upstream to downstream for each reach in the river system.

Besides that, unsteady flow data consist of boundary conditions (external and internal) and initial conditions. Boundary conditions must be specified at all of the open end of the river system. They can also be settled at its internal locations. At the beginning of the simulation, the internal conditions – flow and stage – are required at all nodes of the system.

1.8.14- HEC-GeoRAS

Recently, a geographic information system (GIS) interface called HEC-GeoRAS has been developed at the University of Austen, Texas, by improving a previously issued Arc-View extension (AV-RAS) (Maidment and Djokic, 2000). According to Tabyaoui et al, (2014), HEC-GeoRAS makes easier the gathering of physical data required by the model from a high resolution DEM (USAC, 2009). The extension allows users to create an HEC-RAS import file containing geometric data from an existing digital terrain model and complementary data sets. Results exported from HEC-RAS may also be processed.

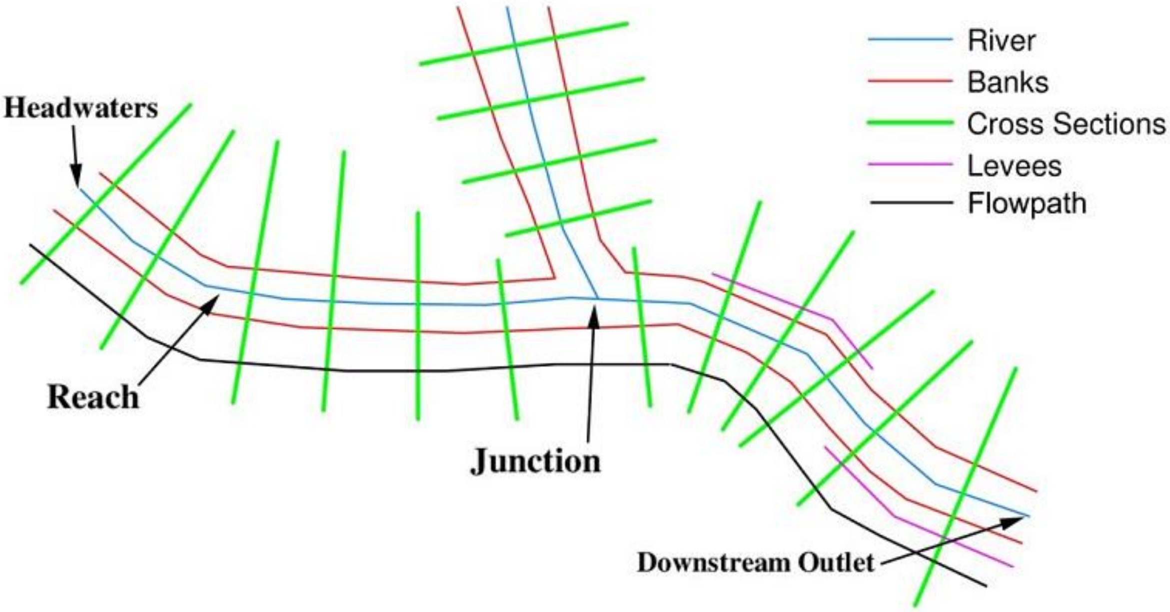


Figure 11: Definition of the channel and floodplain geometry in HEC-GeoRAS (Heimhuber, 2013)

This modelling extension allows to cope with quasi-2D aspects of flow through connecting the river geometry with a digital terrain model in the form of a Triangulated Irregular Network (TIN). In this way, the distributed output provided by HEC-RAS for each cross section is interpolated between cross sections and results in a water depth and a water velocity surface.

Due to its capability of describing that wide range of physical processes it has proven very helpful in supporting all phases of river management planning. When compared with a fully-2D flow model, the only limitation is in giving a flow velocity which disregards transversal components of the flow field vectors, on their side usually deemed negligible in stream hydraulics.

Based on the above sketched model, it is possible to map with appreciable realism the morphology of river and floodplain and to detect the flooded areas for a discharge and flood hydrograph with given return period. The model HEC-RAS delineates a fully functional modelling environment which allows to cope with virtually all types of problems concerning river networks.

Chapter 2: Study Area

Delimitation of Oued Fez watershed and its sub watersheds

Morphometric index of the watersheds

Topographic characteristics and hypsometry of the watershed

Geology and Hydrography of Fez

Climatic characteristics

Fez is the fourth largest city fin Morocco. It is situated 33°58’N 04°59W, at 571 m above the sea level in a valley between the Atlas Mountains in the South and the Rif mountains in the North (Couscous et al., 2015). Fez consists of two contrasting parts: the traditional Arabic-Islamic, medieval city centre, the Medina, and the modern city with its roots in the French colonisation, *la nouvelle ville* (Hans et al, 1998).

The city of Fez is situated at an altitude of 387 m, at the convergence point of four major natural regions, and at the crossroads of two major parties of Morocco: the Middle Atlas to the south, the Atlantic plains in the west, the Rif northern and the eastern highlands opening wide passages to the Tafilalet. Its site is located in the foot of the Tghat Mountain (837 m) and that of Zalagh (900 m) where the course of Oued Fes, after crossing the marshy plain of Sais, accelerates to join the Sebou River.

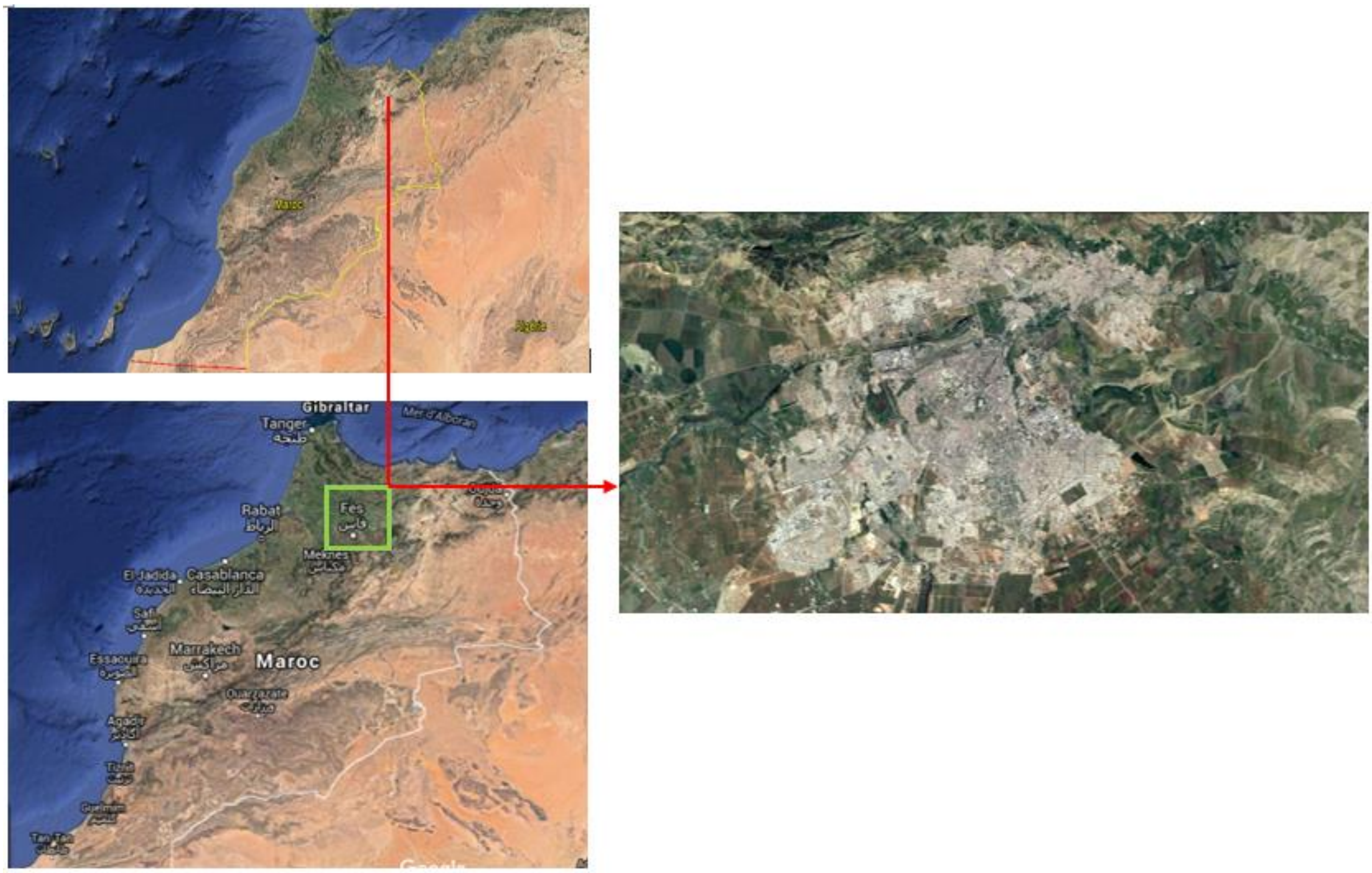


Figure 12: Study area

2.1- Delimitation of oued Fez watershed and its sub basins

2.1.1- Oued Boufekrane

With an area of 52 km^2 and a length of 29 km, the oued Boufekrane takes his source from El Kanntra basin, located on Jbel Ksiksou and the Sefrou dir. This watershed represents the eastern limit of the oued Fez and the Saiss plateau. The Oued Boufekrane drains the Southeastern part of Fez, extending from El Gaâda plateau. It converges to Oued El Mehraz and form a braided bifurcating hydrologic system that, in downstream, influence the lowest part of the Aouinate El Hajjaj district. Boufekrane also converges with Oued Zitoune in the entry of the Rçif district (in the ancient Medina). Its outflow is weak, but the discharge becomes torrential in periods of strong rainfall causing the flooding risk along Oued Boufekrane, mainly in the Aouinate El Hajjaj district.

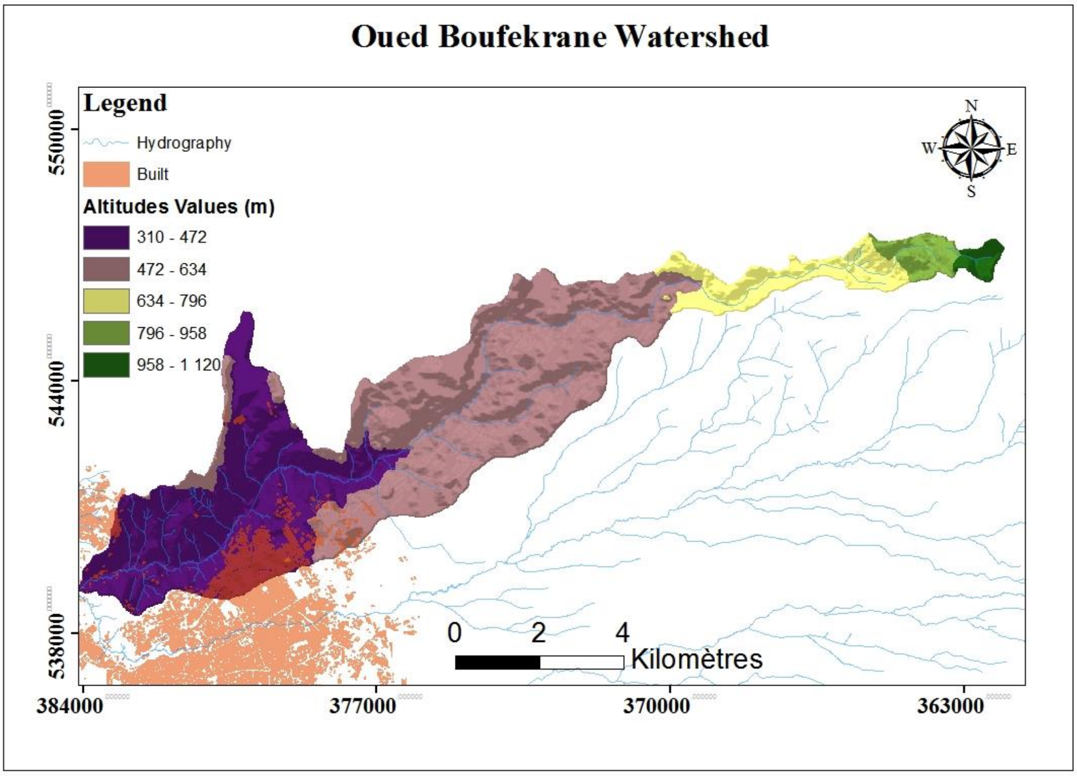


Figure 13: Oued Boufekrane Watershed

Photo 6: Oued Boufekrane dyke

Photo 7: Oued Boufekrane Watershed

2.1.2- Oued Mehraz

Downside the dam, in the urban area of Fez, the Oued El Mehraz valley is only 50 meters wide. The reduced capacity of the channel to convey water during high flows in this transect increases the height of the water surface, and causes the banks inundation, and therefore the flood hazards. The geomorphic hydraulic geometry of the channels is trapezoidal but the valley is dissymmetric because the western's gradient is more important. The oued flows on 29km of length and drains a watershed of 137 km2. It is bordered by Oued Boufekrane watershed in the east, and in the west by El Himmer watershed. The Oued El Mehraz dam construction was a new hydrologic parameter as it regulates water flow and sediments' deposition, but it becomes ineffective in periods of intense rainfall when the dam's retaining capacity is exceeded.

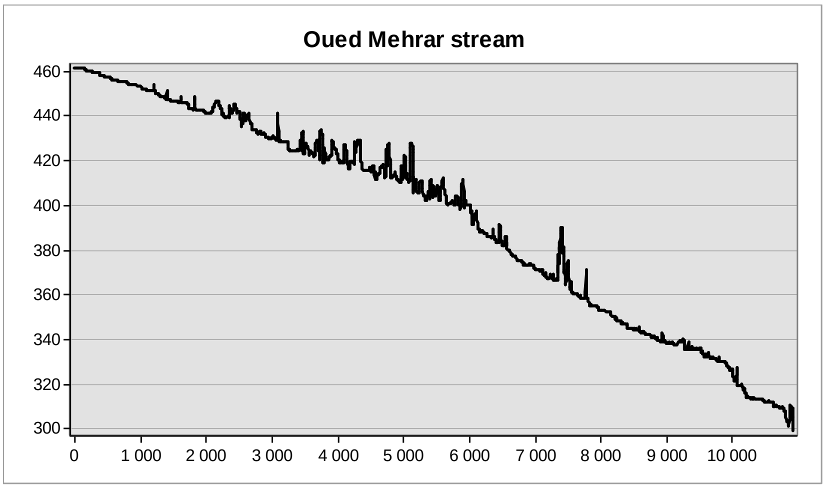


Figure 14: Oued Mehraz stream profile

Photo 8: Oued Mehraz stream, dam and drainage canal

2.1.3- Oued El Himmer

Oued El Himmer is located between oued El Mehraz in the east and between Oued Chekkou in the west. With a length of 38 km, it covers an area of 80 km^2 and represents the watershed the most elongated watershed.

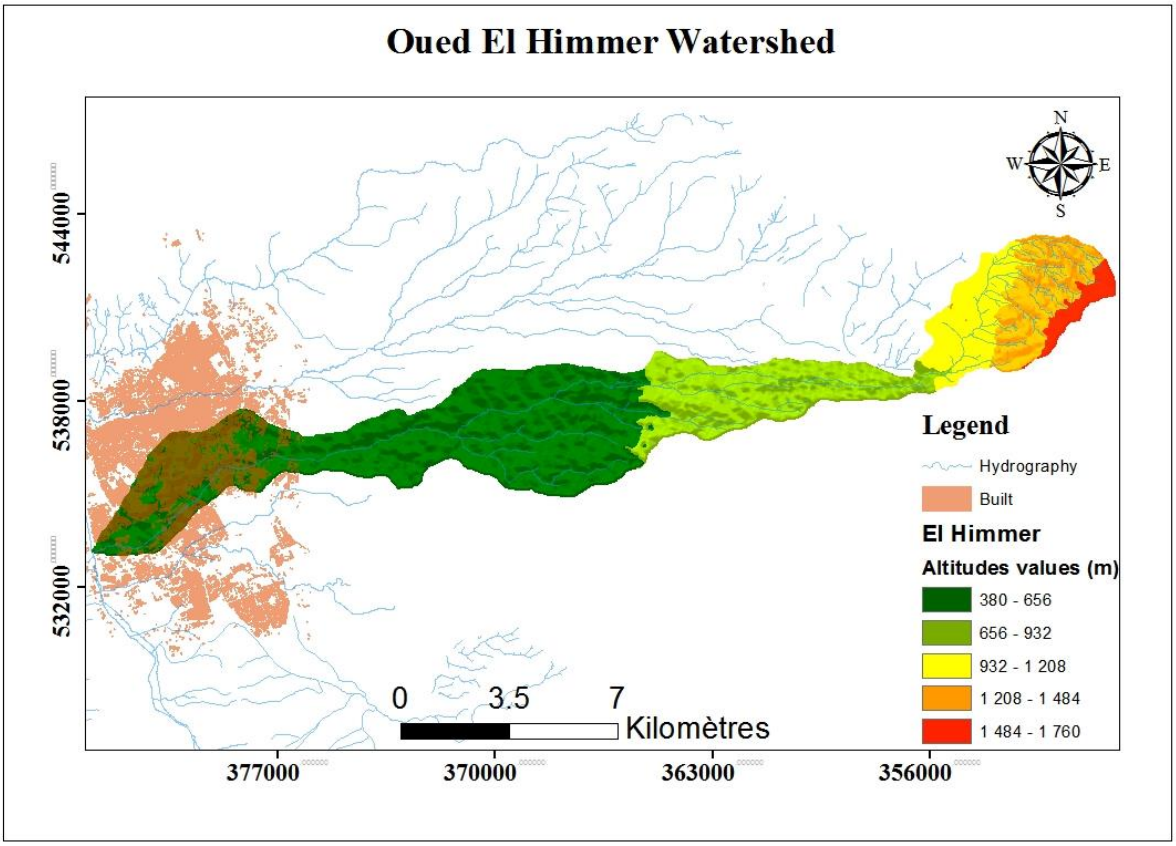


Figure 15: Oued El Himmer Watershed

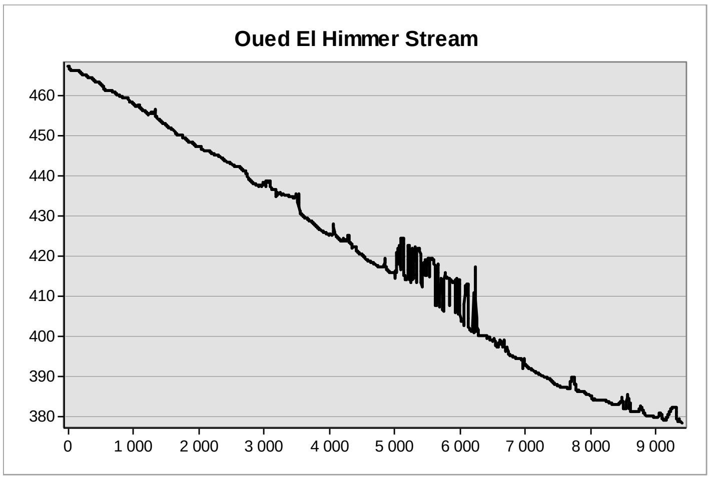
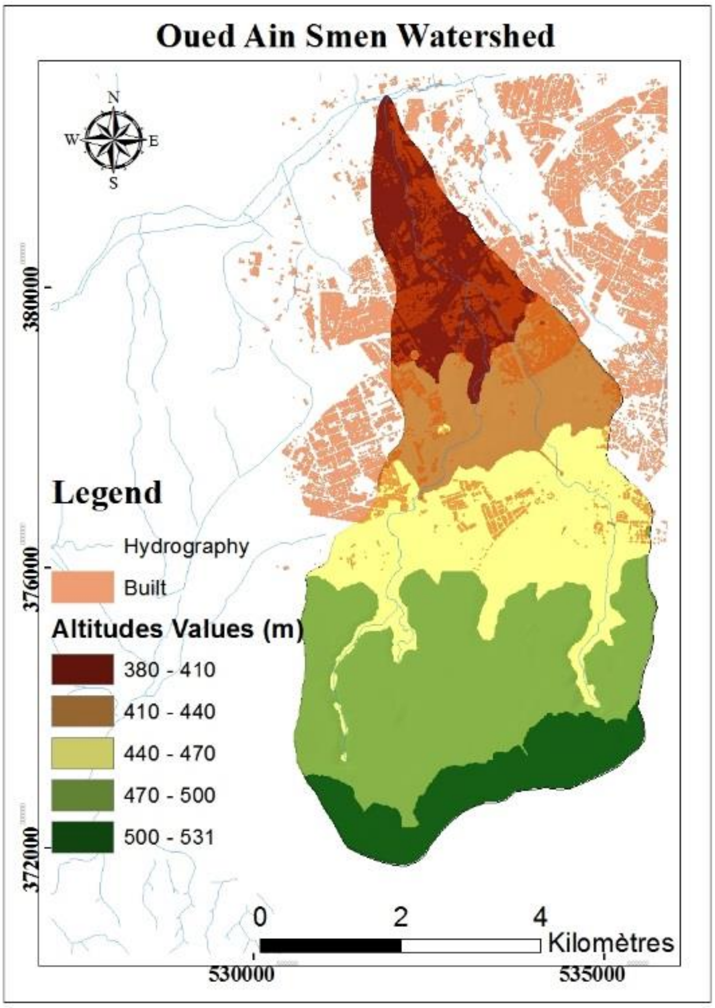


Figure 16: Oued El Himmer Stream Profile

2.1.4- Oued Ain Smen

This watershed is located to the western part of Fez watershed and bordered by El Himmer watershed to the east. It covers an area of 33 km2 and encompass Smen and Chkeff stream. They form a junction upstream and supply Oued Fez watershed.



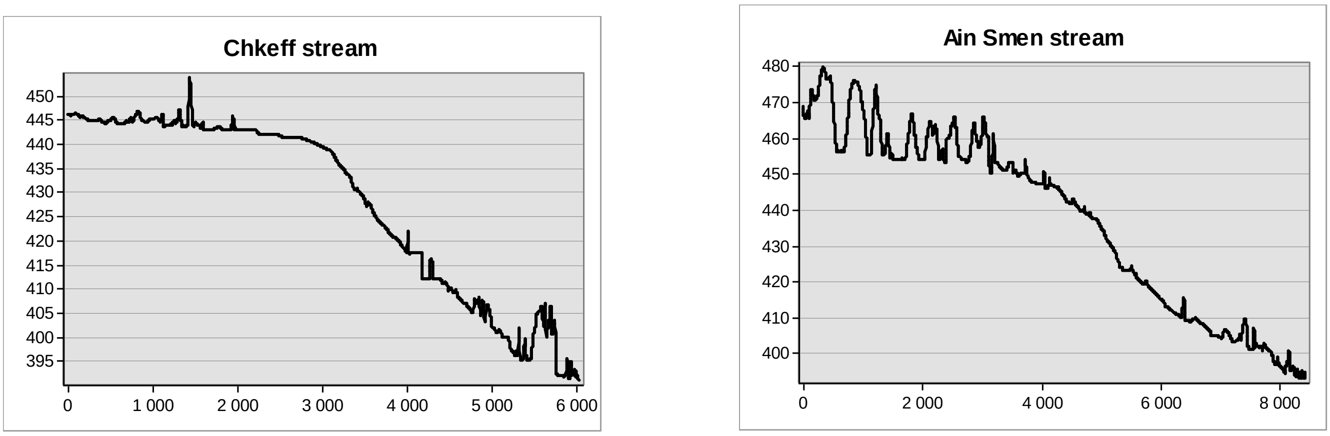


Figure 17: Oueds Ain Chkeff and Ain Smen Streams' profile

2.1.4- Oued Fez

Oued Fez has a South West – North East direction crossing the city of fez and its medina on 24 km length. The Fez watershed can be divided into two entities regarding the hydro geomorphological aspect: the upstream oued Fez and the downstream oued fez. The upstream Fez watershed is supplied by several tributaries such as Oued Chekkou, oueds Ain Chkef and Ain Smen, Oued El Himmer and Jbel Tghat. The downstream Fez watershed, receive some of its waters from the oueds El Mehraz and Boufekrane located at the entrance of Fez Medina. Within the Medina, the watershed drains a channel for a discharge capacity varying between 50 and 80 m^3/s. At the end of the medina, the downstream oued fez flows and reaches the Oued Sebou watershed.

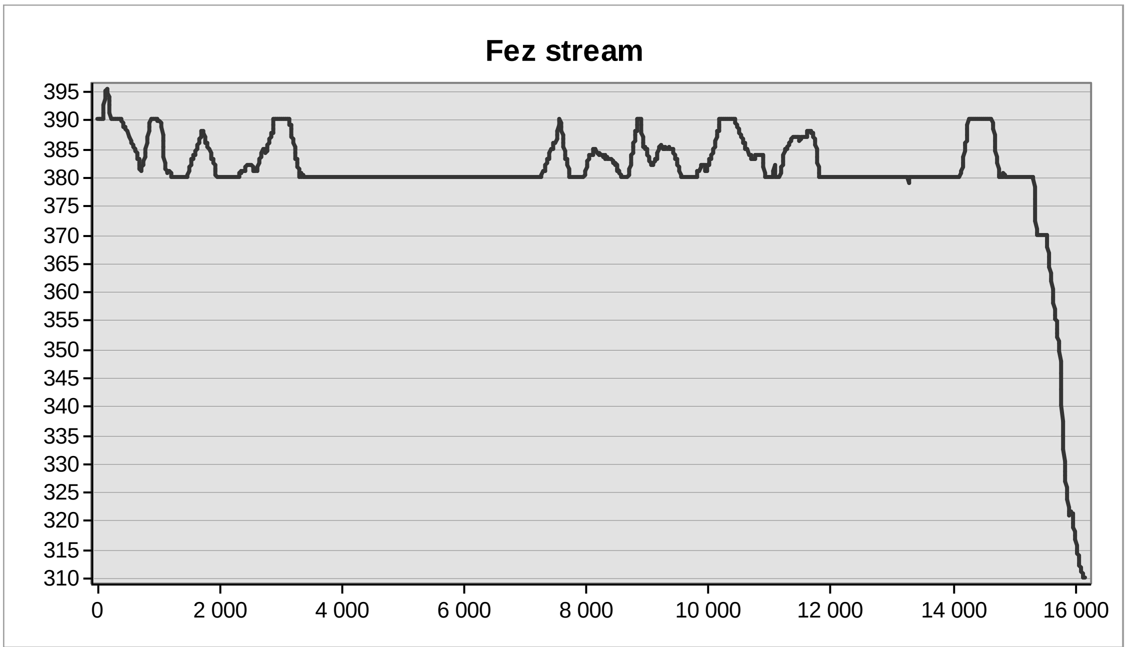


Figure 18: Oued Fez Stream Profile

2.2- Morphometric index of the watersheds

The morphometric characteristics (size, shape…) of a watershed influence the hydrologic phenomena occurring in the watershed. To characterize a drainage basin, several computation methods are proposed within the literature. Roche, 1963; Bravard and Petit, 1997; Taous, 2005; Giret, 2007… The most commonly index referred to is the Gravelius compactness coefficient.

2.2.1- Gravelius Compactness coefficient (K_G)

This is the ratio of the perimeter of the watershed to the circumference of a circle whose area is equal to that of the given drainage basin.

$$K_G = 0.28 \frac{P}{\sqrt{A}}$$

Where P is the perimeter and A the area. This index is determined after delimitation of the watershed and measurement of its perimeter and surface area. K_G is equal to 1 for a watershed almost circular and greater to 1 for a most elongated shape. It is presumed that more the watershed is elongated, more the time for the water to reach the outlet increased.

2.2.2- Length and wide of the equivalent rectangle

$$L = \frac{c\sqrt{A}}{1.12} * \left[1 + \sqrt{1 - (\frac{1.12}{K_G})^2}\right]$$

$$l = \frac{A}{L}$$

The following table outlines the geometric characteristics of Fez watershed and its sub basins:

Table 3: Oued Fez watershed geometric characteristics

Watersheds Characteristics	Oued Boufekrane	Oued Mehraz	Oued Himmer	Oued Ain Smen	Oued Fes
Perimeter (km)	63.14	75.71	80.03	27.56	207.11
Surface Area (km2)	52.4	137.7	80.74	32.98	879.37
Gravelius Compactness coefficient	2.44	1.81	2.49	1.34	1.96
Length of equivalent rectangle	29.81	33.78	37.88	10.70	94.22
wide of equivalent rectangle	1.76	4.08	2.13	3.08	9.33

2.3- Topographic characteristics and hypsometry of the watershed

The effects of the topography, the hypsometry and the energy of the relief, need also to be considered when it comes to analyse the hydrologic response of a water body. That is due to the fact that several parameters vary with the climate (considering the altitude) and the flow velocity. Within the Fez watershed, there are three (3) topographic entities known as: the Middle Atlas (‘*la cause du moyen Atlas’*) in the south, the Saiss plain and the Prerif ridges (‘*les rides prérifaines’*).

The Middle Atlas is located in the south and represents the highest elevation zone. It is situated between the Rif range to the north and the High Atlas range to the south (Du Dresney, 2005). The Middle Atlas is part of the Atlas Mountain range in central Morocco, lying between a plateau and plain region (Northwest); and the main part of the Atlas Mountains (Southeast). It’s a solid mountainous mass of 350 km in length in the North-East of Morocco. This entity is constitutes of Lias limestone and dolomites and Triassic clay. The Saiss plain represents a relatively flat topography (400 – 700 m), with a slight slope (0.1%) from the south to the north. The cross bedding, appearing as a mountain relatively high, for instance Jbel Tghat (860m) and Jbel Zalagh (900m) which are located in the north of the watershed.

2.4- Hypsometry of the watershed

Hypsometry is the frequency distribution of land area at different elevations. For example, Earth's hypsometry is bimodal, with the majority of area at elevations of either continental platforms or ocean basins. The hypsometric map of the watershed allows to analyse the variation of the altitudes which influences the velocity of the water; for the fact that a considerable slope leads to higher discharges. In Fez watershed, the hypsometric map presents five (5) altitudes values from 195 to 1760 m. The map has been obtained from the Digital Elevation Model (DEM) of the watershed.

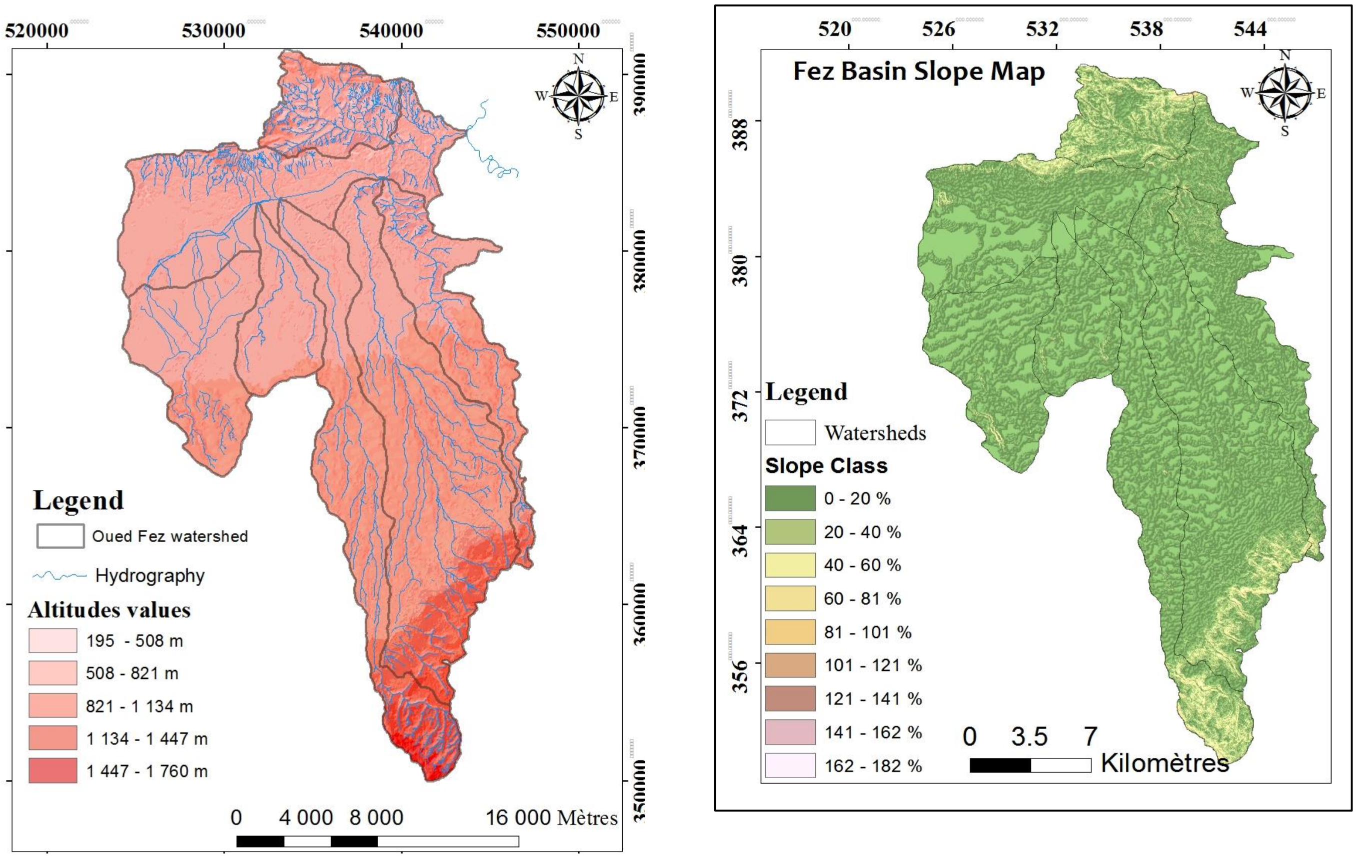


Figure 19: Hypsometry and slope of Oued Fez Watershed

The mean slope determines the velocity at which the water will flow to the outlet of the watershed and consequently impact on the lag time. The lag time or time of concentration influences then the maximum discharge. A considerable slope will increase the runoff, where as a low slope will allow the water to infiltrate.

2.5- Geology and Hydrography of Fez

The geology of the city of Fez is characterized by the presence of lacustrine limestone, clay-limestone tuffs and conglomerates on set, silt in the alluvial terraces of the Sebou Valley, travertine, marls, and conglomerates in the valley, debris of limestone slopes, limestone, sandy loams, tuffs and conglomerates on north glaze reliefs, and blue marls altered on the southern hills. The soil of the city, especially at the sub watersheds favours the runoff instead of infiltration (low infiltration). The natural vegetation of the city of Fez is composed of plants adapted semi-arid climate.

Besides that, the hydrology of the Fez region is characterized by a hydrographic system (figure 20) focused on Fez which flows from West to East, from its sources of Ras El Ma to Sebou crossing the old medina of Fez, the Oued Fez receives several tributaries throughout its path towards the Sebou river, and are fed by resurgences of groundwater as the Oued Mahraz, Oued Miyet and Boufekrane, and others that drain essentially runoff water: Oued Mellah, Oued Smen, and Oued Ain chkef [3]. It is limited to the north by the line of ridges corresponding to the pre-Rif wrinkles, to the west by the basin of Oued Nja, on the east by the Sebou basin and southerly by the cliffs of the Middle Atlas Causse Immouzer.

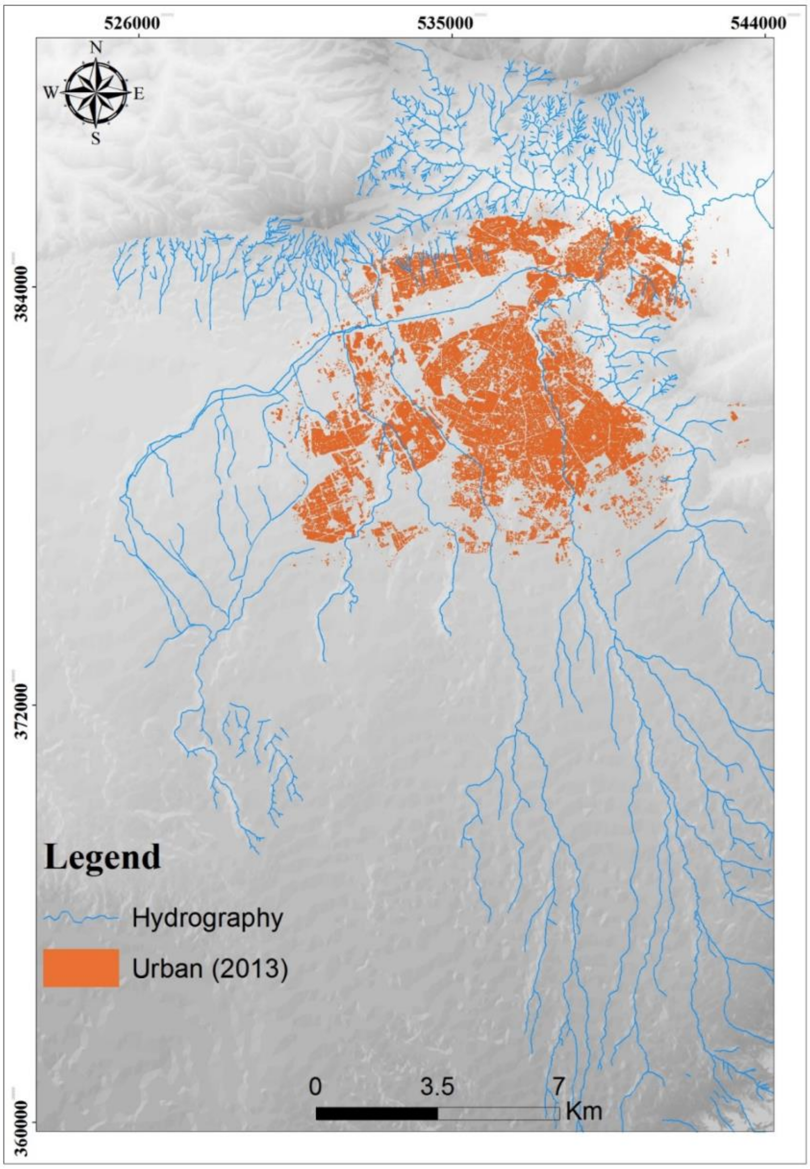
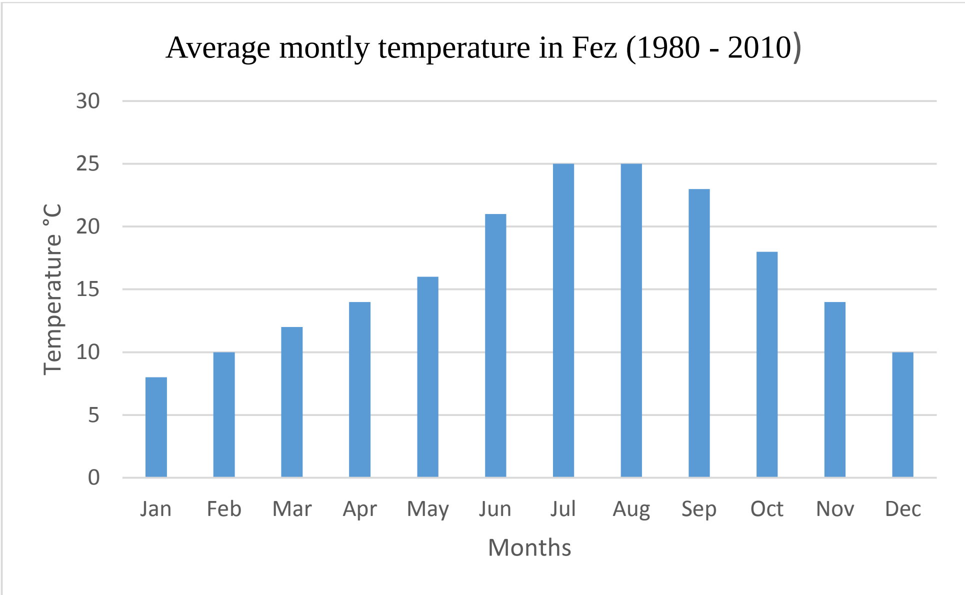


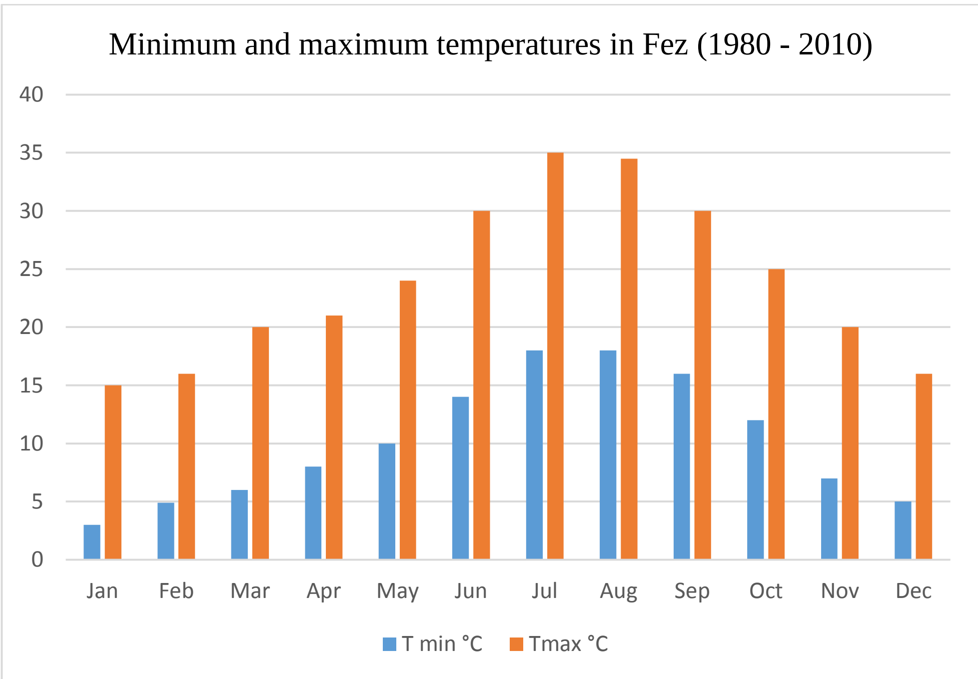
Figure 20: Hydrography of Oued Fez Watershed

2.6- Climatic characteristics

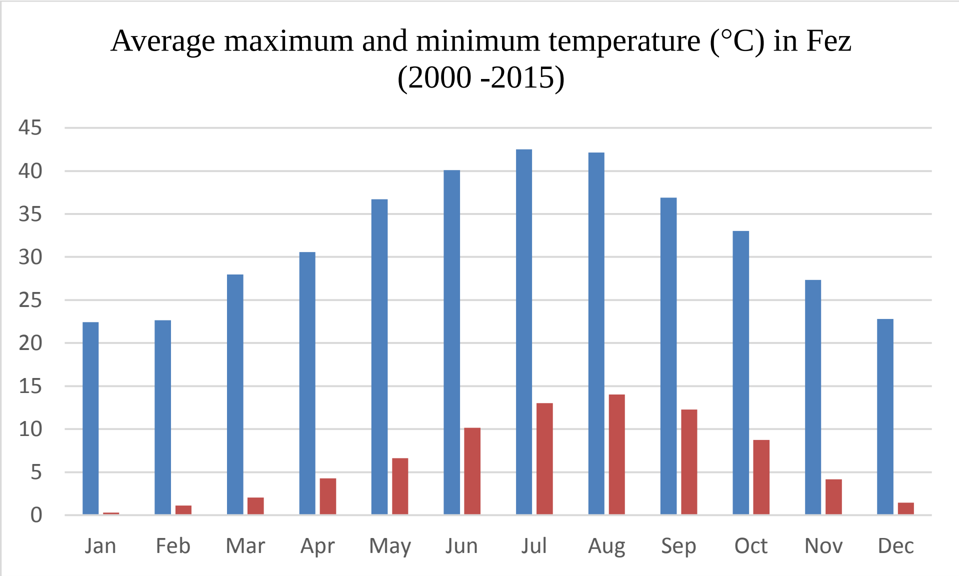
The climate of Fez is characterised by hot and dry summers and cold winters with rare snow. Annual mean temperature is 17°C with a high thermal difference between the mean minimum of the coldest months (January 4 ° C) and maximum of the hottest month (July: 34 ° C). The climate of the region is semi-arid, the average annual rainfall is about 500 mm on the Sais basin. It has a considerable variability between 1980 and 2014.



Graph 3: Average monthly temperature in Fez (1980 - 2010)

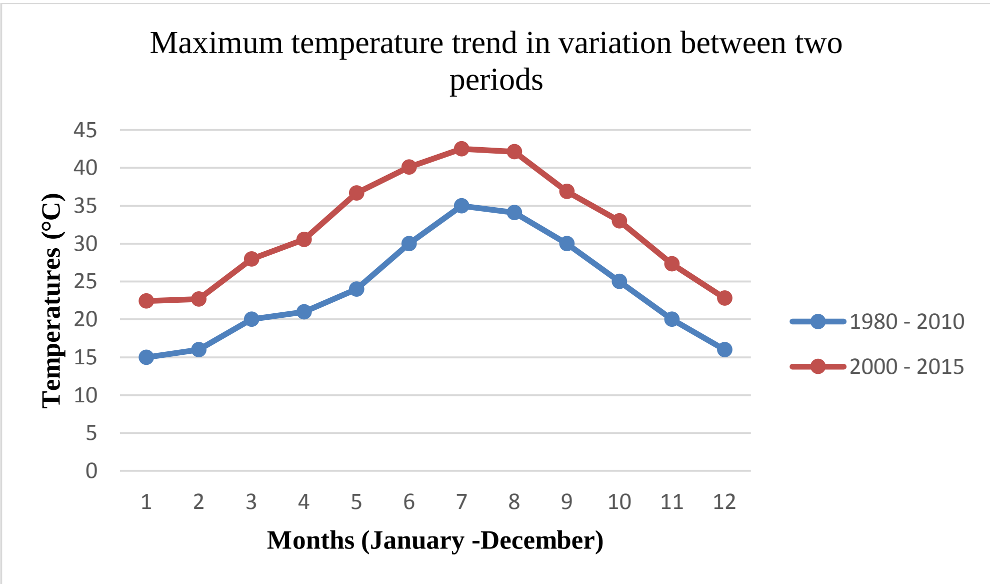


Graph 4: Maximum and minimum temperatures in FEZ (1980 -2010)

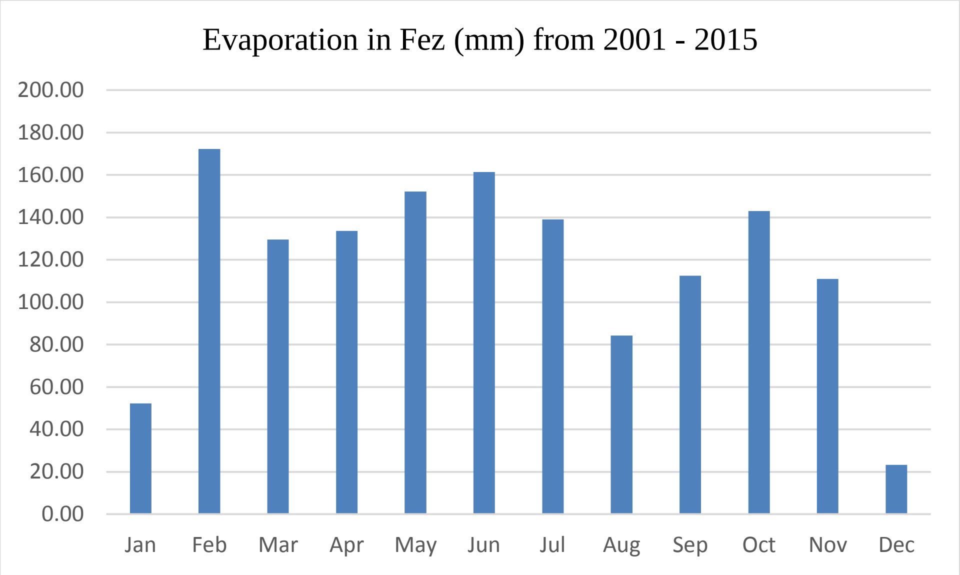


Graph 5: Average extreme temperature in Fez (2000 - 2015)

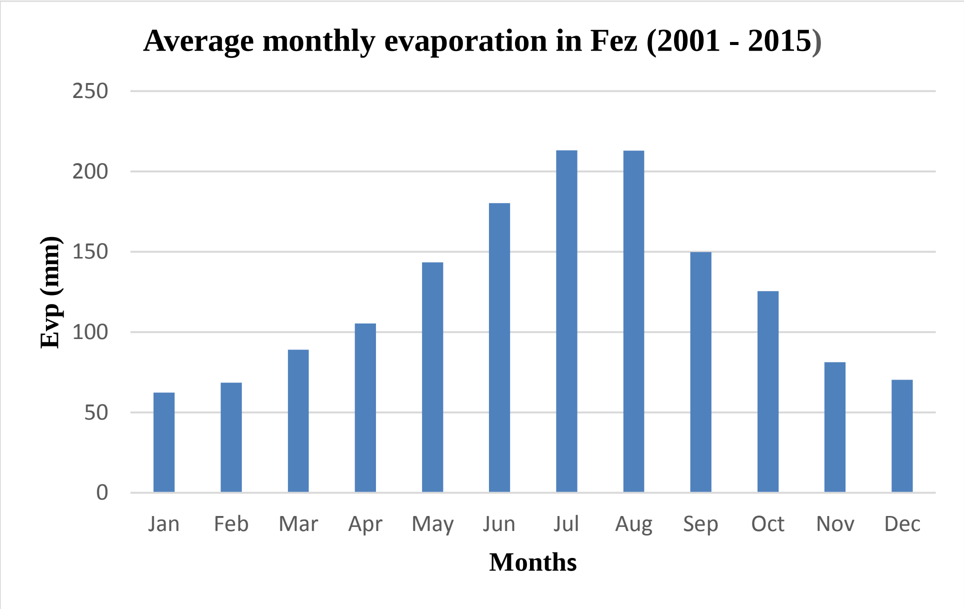
If we combine the two graphics (4 and 5), we can easily notice that there is a change between the two periods (1980 to 2010) and (2000 to 2015) with an increase of temperature for the maximum values. The minimum temperatures also decrease considerably from the first period comparing to the period between 2000 and 2015. The trend is showing below:



Graph 6: Temperature variation in Fez between two periods



Graph 7: Average monthly Evaporation (2001 - 2015) at Fez Saiss station



Graph 8: Average monthly Evaporation in Fez at Meknes station (2001 – 2015)

The graphs obtained from the evaporation data confirm in a sense the temperatures trend in Fez: during the warmest month, the evaporation is high and the coolest month has a lower evaporation. As Trenberth in 2005 explains, there is a direct influence of global warming on changes in precipitation and heavy rains. Increased heating leads to greater evaporation and thus surface drying, thereby increasing intensity and duration of drought. However, the water-holding capacity of air increases by about 7% per 1 ◦C warming, which leads to increased water vapour in the atmosphere, and this probably provides the biggest influence on precipitation.

Chapter III: Hydrologic Response of the Watershed

Reconstitution and analysis of historical floods events in Oued Fez

Frequency analysis of annual rainfall events

Time of concentration and Peak discharges

The first part will focus on the analysis of the different historical flooding event in the medina of Fez owing to the fact that historical events are very useful to understand the risk behaviour, i.e., the hydrological hazard and the impacts it causes on people and the environment.

The next section sheds light on a statistical technique use to estimate rainfall depths that can be expected for selected probabilities or return periods. With the help of a frequency analysis on historical rainfall data, the magnitude of the rainfall depths can be estimated. The estimates are required for the design and management of irrigation and drainage projects. In addition, probability plots are extremely useful for visually revealing the character of a dataset. The tool used in this case study is Hydraccess, a software which allows to import and manage various kind of hydrological data in a Microsoft Access 2000 database, and to realize all processing that is needed. It also makes use of the well-known Excel spreadsheet.

Finally the time of concentration and the peak discharges of the watersheds will be estimated using different empirical formula. The time of concentration which measures the response of a watershed to a rainfall event is important and useful in predicting the flow rates that would result from storms.

3.1- Historical floods events in fez

This part of the work will consist of the computation of the lag time using different empirical formula and the estimation of the peak discharge for different return period. Before that, historical flooding events in fez city will be analysed.

3.1.1- Flood event of September 1950

According to the *Public Work Department*, the flood event of 26th September 1950, is the most disastrous event occurred in the city of Fez. The same source reported that at the plateau of Saiss, the oued Mehraz flood announced itself at 2km by an audible roar which allowed some people to avoid human damages. The fury of the flood of Oued Mehraz destroyed several houses and localities of Montfleuri and Sidi Brahim with its peak discharge estimated at 500 m3/s at the entrance of Monfleuri and led to a pregnant woman depth (*Public Work Department*, 1951). Fortunately, the flood caused less damage in the medina of Fez due to the dam of Dhar El Mehraz which retains a great amount of the flood. That hydraulic structure has a height of 22 meters and a capacity of 1,700,000 m^3. However, it was full during 4 hours, from 7:00 p.m. to 11:00 p.m. and became empty in 3 hours, from 11:00 p.m. to 2 o'clock, thanks to a drainage gallery of 115 m^3/s of capacity.

Oued Himmer flood with an estimated discharge of 150 m^3/s has also created several material loss and destruction of considerable amount of cultures. In addition to that, Oued Chekkou has generated damages as well with a discharge less than 150 m^3/s but during a long period of time (*Public Work Department*, 1951).

3.1.2- Flood event of October 1989

The tributaries of oued Fez, in the evening of October 13rd, 1989 had known brutal and sudden floods; causing damages in the agglomeration. It has been reported that Oued Mehraz has generated the most severe flood with a discharge of 150 m^3/s; according to the *DRH Sebou*

(1989). That discharge flooded the whole path of the watershed which is already highly populated. According to statements recorded by the social authorities of the agglomeration, people have been surprised by an important flood at 8:00 pm, followed by a smaller flood at around 3:00 a.m. The considerable overflow of that flood has been noticed on the bridge of Sefrou road which scuppers could not resist on the flow of the water. Consequently, the water passed through the road also and houses on the right bank have been invaded by water and mud. According to *DRH Sebou* in 1989, cars have been through away on a 200 meters distances due the water velocity.

Besides that, Oued El Himmer and Oued Boufekrane floods were less considerable with a peak discharge of 50 m3/s and 20 m3/s respectively. El Himmer flooded several localities such as Oulad Tayed, Zouagha and Karim Amrani, while Boufekrane inundated the entrance of the medina of Fez due to the overflow of the draining channel of Bab Jdid.

The table below sums up the water height recorded in different stations for the 1989 flood in the watershed of Fez:

Table: October 13rd, 1989 flood intensity (Lasri, 2013)

Stations	**Sefrou**	**Fez Saiss**	**Ain Bettit**	**Douiyat**	**Fez-ABHS**
Height (mm)	26.5 mm in 30 minutes	69 mm in 24 hours	49 mm in 12 h	15.5 mm in 12 h	28.2 mm in 12 h

3.1.3- Flood event of September 2008

Following the floods event of October in 1989, some infrastructures have been built to ensure a protection against the devastating effects of flood in Fez: El Gaada dam in 1992 on Oued Boufekrane with a retention capacity of 2.8 million cubic meters and Moulay Arafa dam on Oued Mehraz in 1993 with a capacity of 0.6 million cubic meters. This later is linked to Oued Boufekrane through a channel. However, heavy rainfall occurred in September 2008, occasioned the overflow of those infrastructures, which generated flooding of each area within Oued Fez and its sub basins. That flood event of September 28th, 2008 is said to be one of the catastrophic flood within the agglomeration, with a cumulative water height of 104 mm in Fez-Saiss in only 10 days. According to Jonati Idrissi (2010), the disaster can be explained by the collision between polar air masses from Island depression and warm continental air masses coming from the Saharan anticyclone. The city has been flooded by Oued Boufekrane, El Mehraz, El Himmer, Ain Smen and Fez. It is important to mention that the city has not receive any precipitation the day it has been flooded. Several localities have been affected. Among them Aouinat El Hajjal district at the medina entrance by Oued Boufekrane; Monfleuri 1 and 2, Narjiss, Sidi Brahim and Lido districts by Oued El Mehraz. Others neighbourhood and districts such as Lala soukaina, Hey Tazi and Zougha have been flooded by Oued El Himmer.

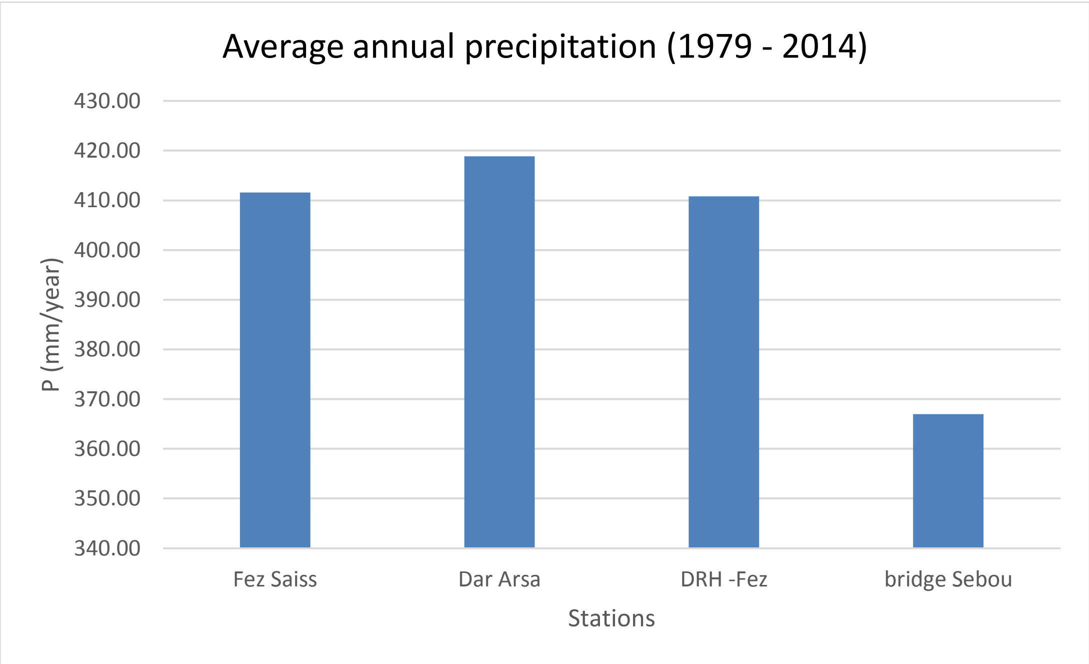
3.2- Variation of the monthly and annual precipitation in Oued Fez watershed

To perform the analysis of the precipitation, which is irregular in the Mediterranean climate, this paper focuses on data gathered from four (4) different stations in the watershed namely Fez Saiss, DRH Fez, Bridge Sebou and Dar Arsa. The choice of these stations is based on their location in the watershed and the quality of the chronological records. The table below outlines the different stations and their coordinates.

Table 4: Pluviometry stations and characteristics

Stations	**References**	**Coordinates (m)**		
		x	y	z
Bridge Sebou	pt Sebou RP 26	52 325	41 220	85
DRH Fez	DRH - Fez	53 540	38 488	415
Fez Saiss	Fez	536 459	389 170	400

The results of the annual variation between the stations are presented below (Graph 9 and Table 5). Bridge Sebou station appears with a great variation, compared to the three stations which have their mean values around 410. 95 mm, 419mm and 410.8 mm; respectively for Fz Saiss, Dar Asra and DRH- Fez.

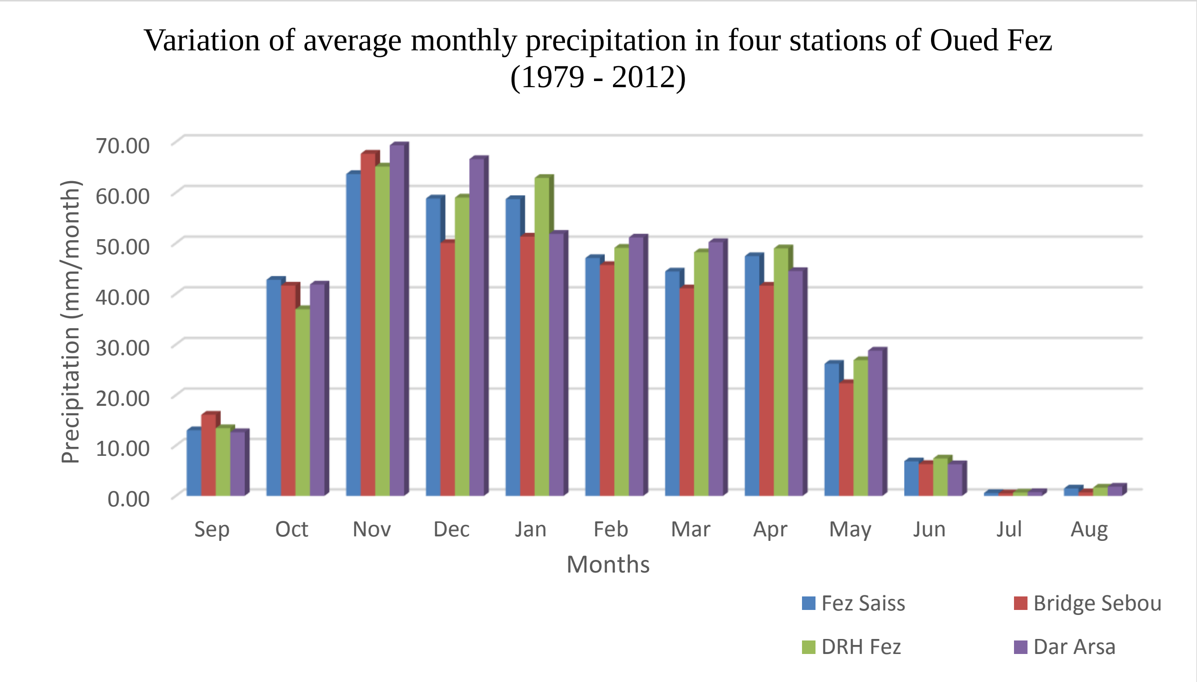


Graph 9: Average annual precipitation (1979 -2012)

The table below presents the extremes to the mean in addition to the standard deviation. It is noticed that the DRH-Fez has the highest variation coefficient compared to the three others stations:

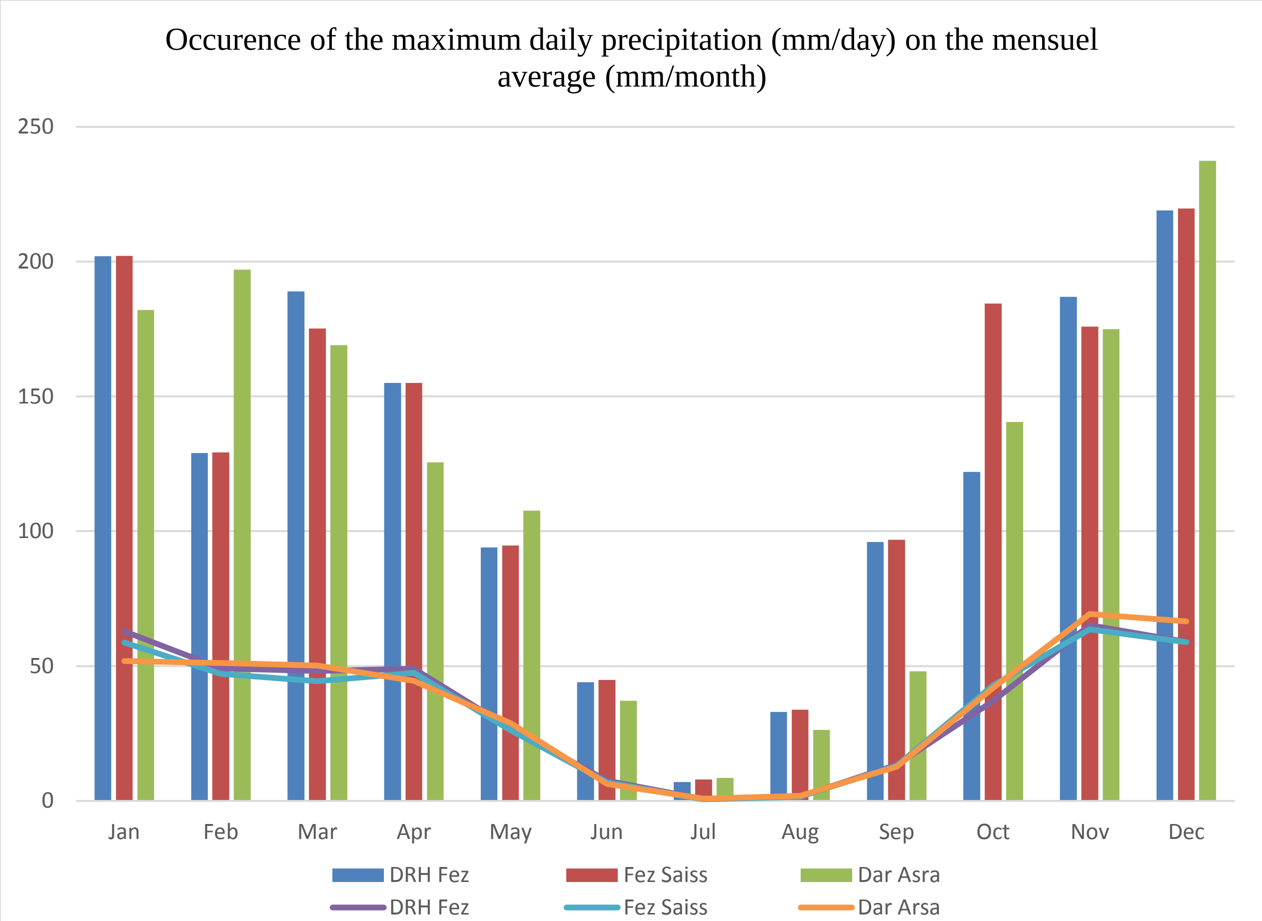
Stations	Mean	Max	Min	Extremes to mean		Standard deviation	Coefficient of variation
				surplus	deficit		
DRH - Fez	410.8	838	181	427.2	229.2	156.7	38%
Fez Saiss	410.95	867.4	185.6	456.45	225.35	151.35	37%
Bridge Sebou	366.96	680	176	313.04	190.96	130.40	36%
Dar Arsa	418.9	791.7	203.5	372.8	215.4	147.07	35%

The average monthly precipitation presents a good trend (graph 10) between the four stations, with the lowest values observed during the warmer months.



Graph 10: Variation of average monthly precipitation in four stations of Oued Fez (1979 - 2012)

The graph 11 compared the precipitations (maximum and minimum) values to the mean. It is noticed that most of the maximum water height occurred during the winter. They seems to occasion the precipitation due to the regional atmospheric disturbance during the winter called frontal precipitation.



Graph 11: Occurrence of Maximum and minimum Precipitation on the monthly average

3.3- Frequency analysis of annual rainfall events

3.3.1- Overview of Hydraccess

Hydraccess is an extensive, homogenous and user friendly software, which allows to import and manage various kind of hydrological data in a Microsoft Access 2000 database, and to realize all processing that a Hydrologist can need. It was developed by a hydrologist for other hydrologists. Its development began in year 2000, and was regularly continued since. Its author is Philippe Vauchel, hydrologist in the IRD (French Research Institute for Development). Hydraccess makes use of the well-known MS Office database (ACCESS) and spreadsheet (EXCEL). Hydraccess makes an extensive use of Microsoft Office automation possibilities. As a result of many functions, it creates Excel workbooks (and sometimes Word documents for water yearbook tables), allowing for the user to obtain data tables and elaborated graphs, that can be customized and directly included in reports.

In addition, Hydraccess offers many possibilities to visualize data, in simple or comparative graphs, that can be freely scrolled in Excel, thanks to a little Excel macro that comes with the software. So the user can visualize the data with a time step convenient to the data variability. The software is suited for data processing from micro watershed to large rivers. For small catchment areas, functions to analyse *Rainfall – Discharge* events and storm intensities are available.

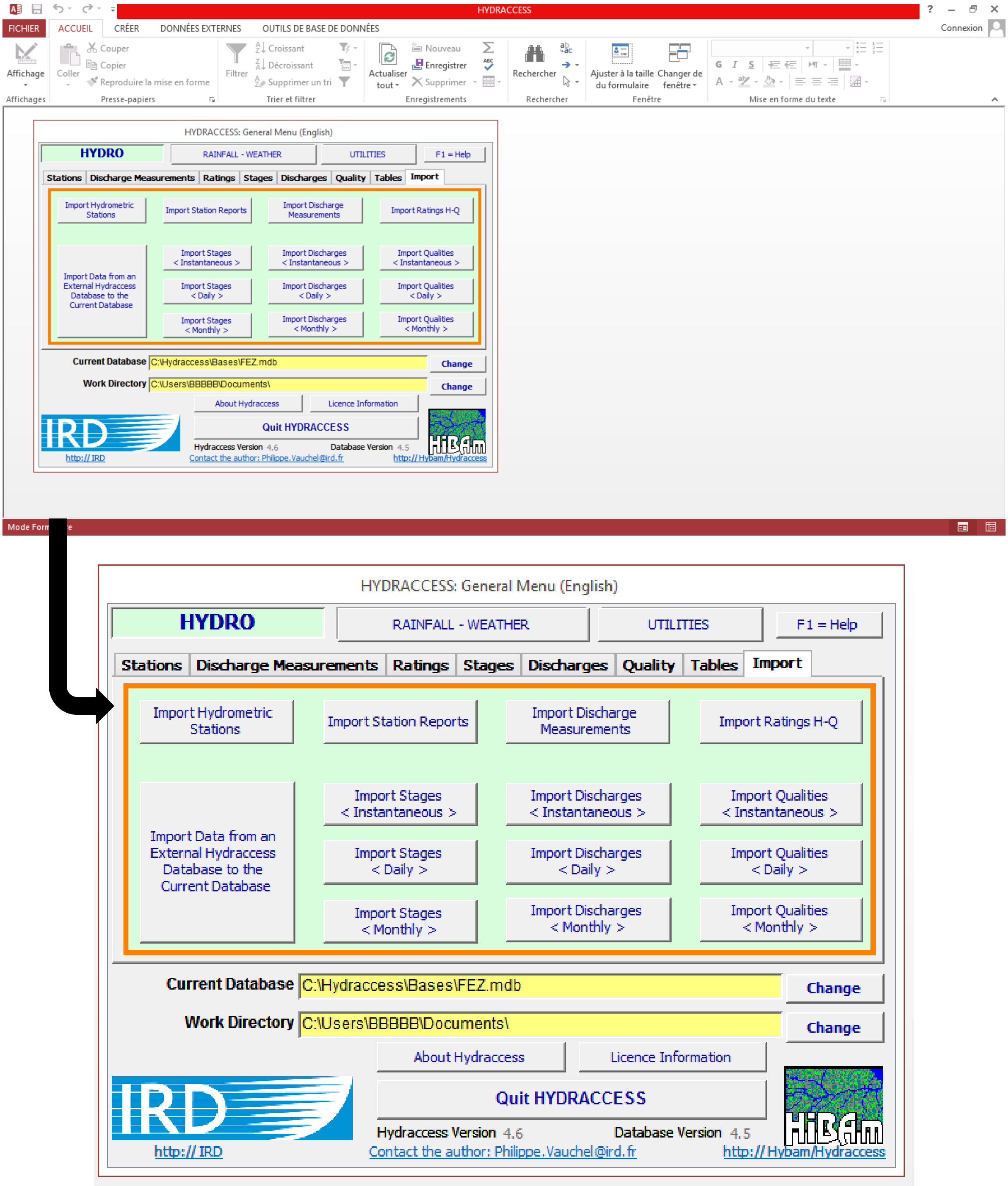


Figure 21: Hydraccess interface

Besides that, Hydraccess can manage the following data:

- **Chronological series**: stages, discharges, water quality, rainfall, meteorological data.
- **Discharge measurements**: discharge as a function of stage, and cross-sectional SM (suspended materials) as a function of surface SM.

- **Rating curves**: discharge as a function of stage, cross-sectional SM as a function of surface SM, solid discharge as a function of liquid discharge.
- **Station reports**: free text data related to station history.
- **Stage gauges general data**, in meters above sea level.

Hydraccess can import data contained in Text or Excel files, provided these files respect an adequate format. In case of *Diagram* input files (chronological data produced by a recorder), Hydraccess offers a module allowing to visualize this diagram, and to perform level or time corrections, before importing it in the database. Time series data as stages, discharges, water quality data, rainfall and meteorological data are organized in different tables. They are linked to a station (a measurement location) and to a sensor (the name of a data series). The sensor has properties allowing to define its description, unit, significant digits and decimals. There are three types of sensors: instantaneous, daily and monthly.

3.3.2- Statistical analysis and fittings of the maximum rainfall

The fittings of the statistical laws on the rainfall data give an estimation of the return periods of the extremes values. That is important for hydraulic works, prediction and prevision of floods. This frequency analysis is based on monthly rainfall data gathered from Fez Saiss station for a period of 33 years, from 1979 to 2012. It has been performed under the "Utilities tab" and "Frequency analysis".

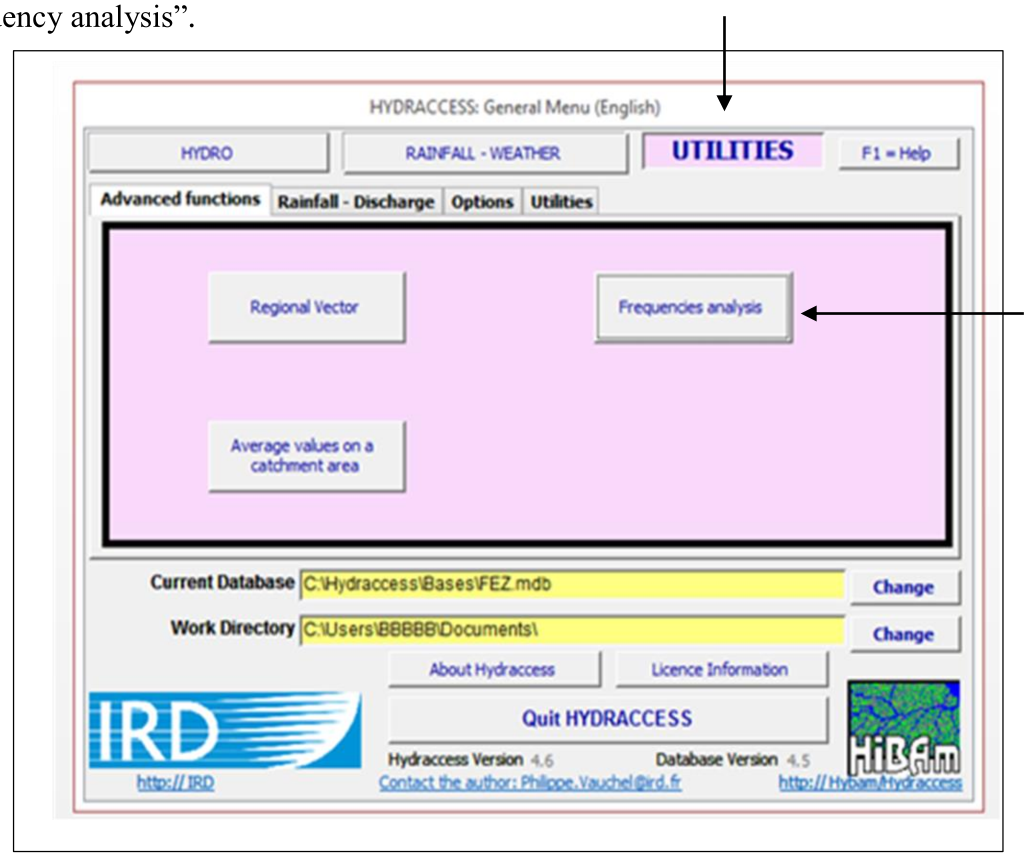
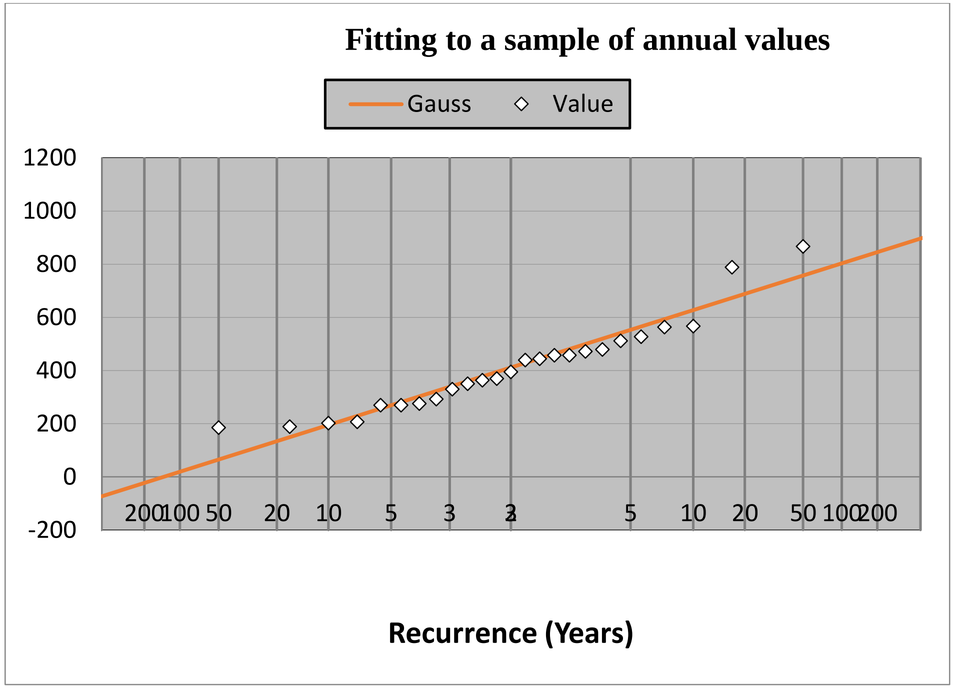


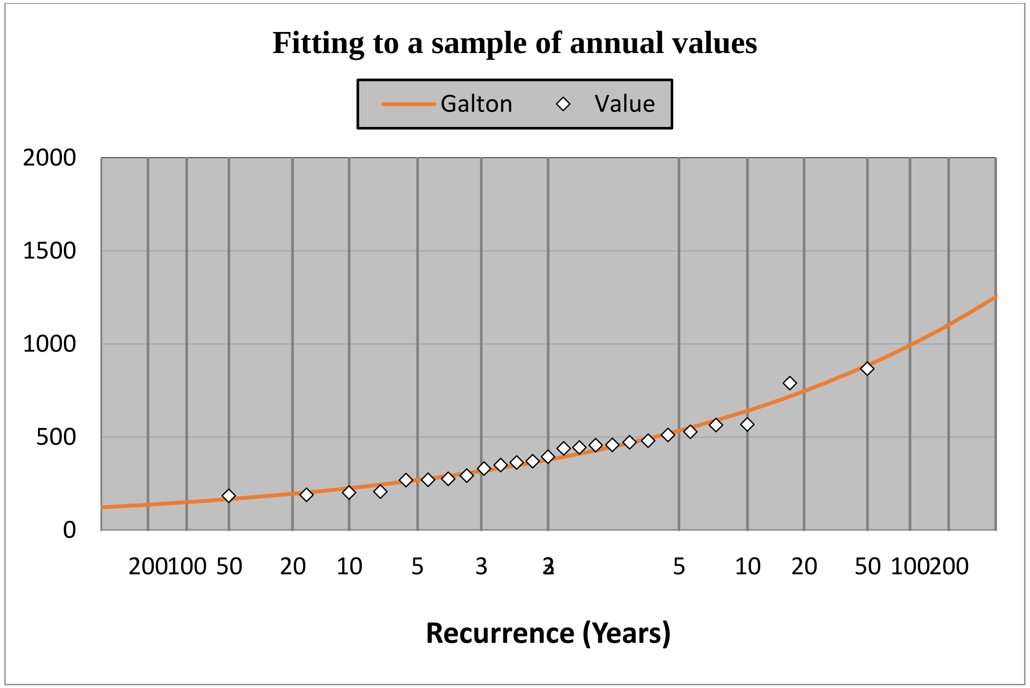
Figure 22: Hydraccess - Utilities tab

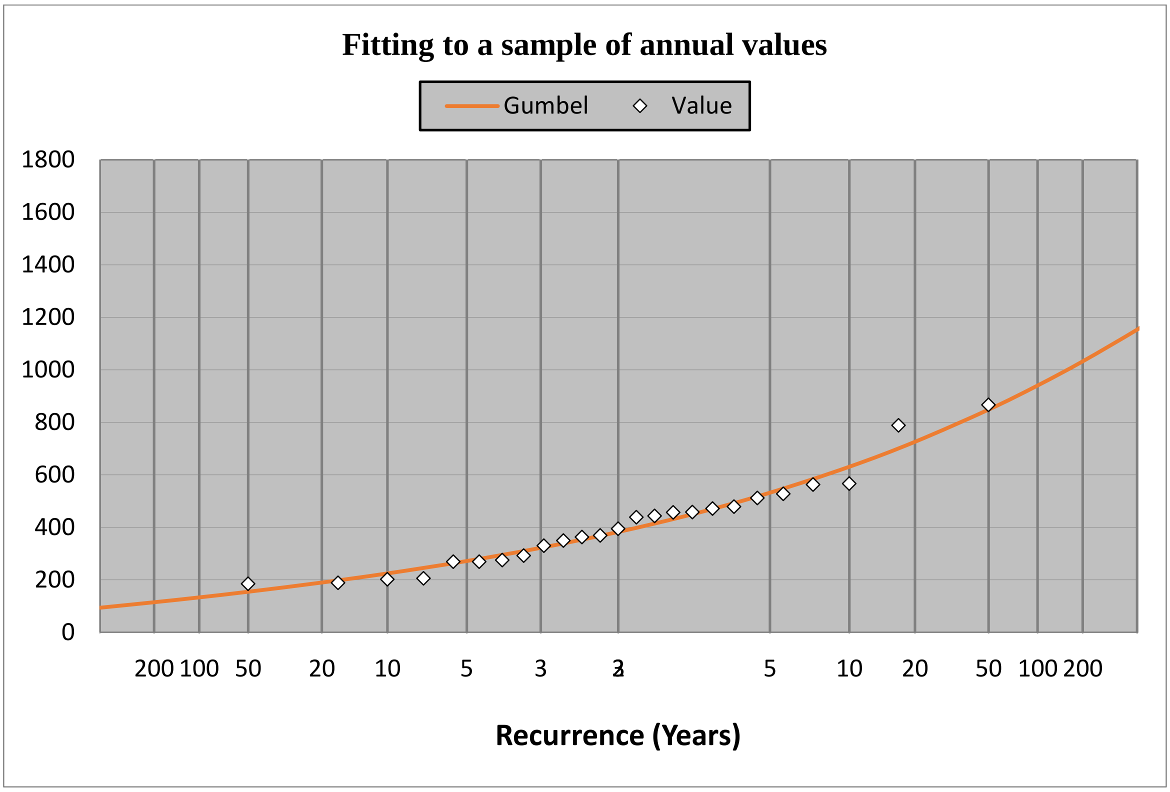
The laws put on test are:

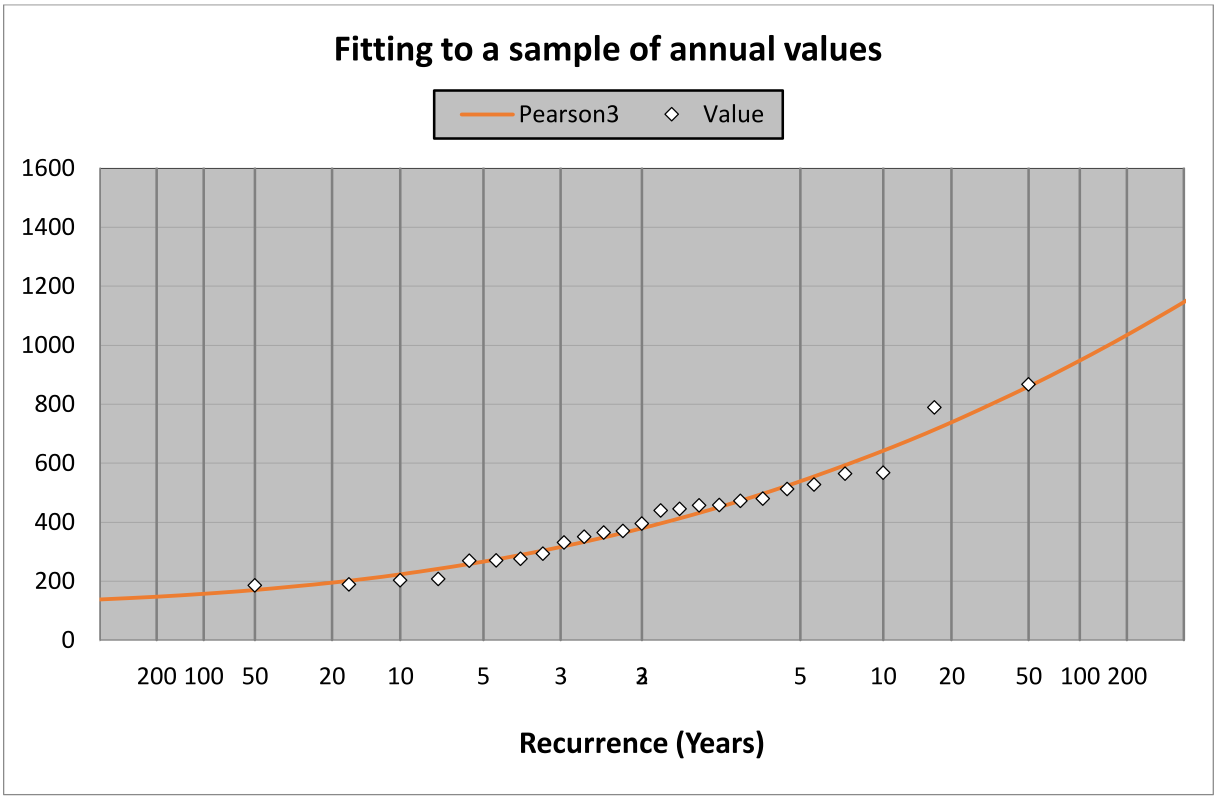
- Gauss (normal law)
- Galton (log – normal)
- Gumbel
- Pearson 3

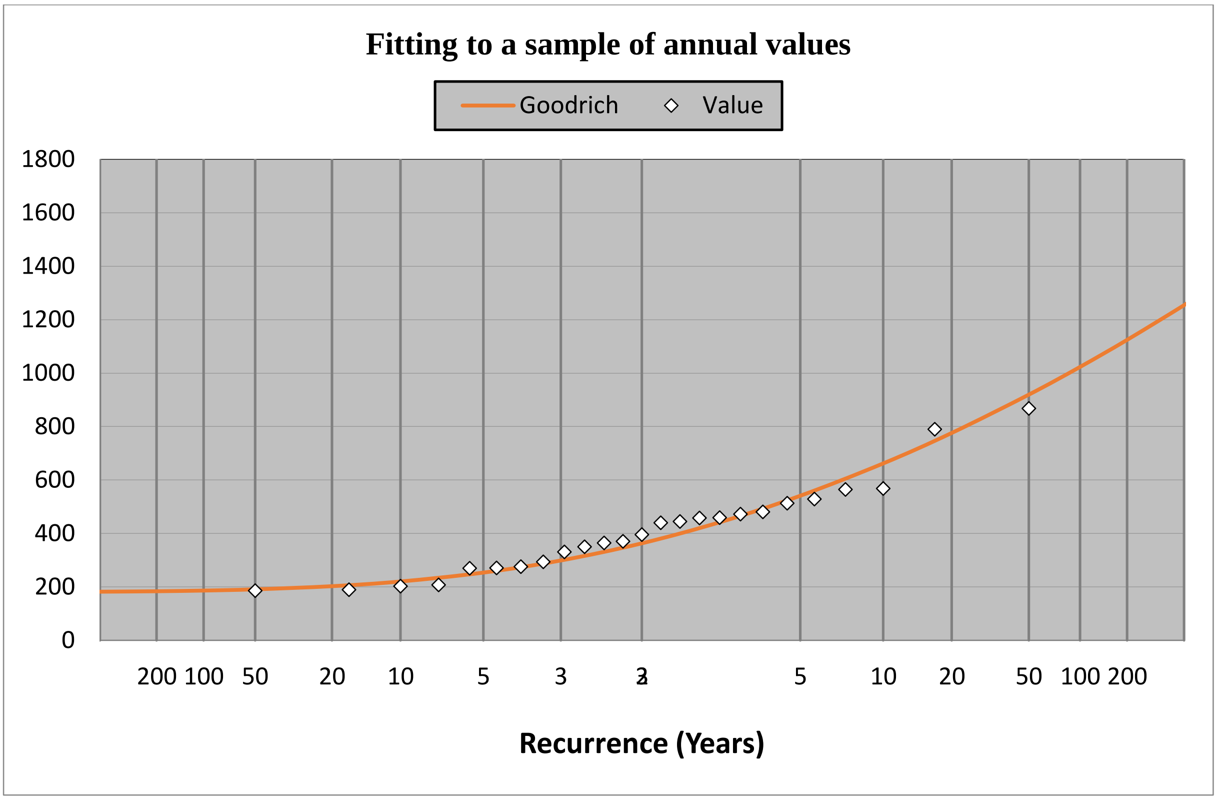
The graph fitting results are presented below:



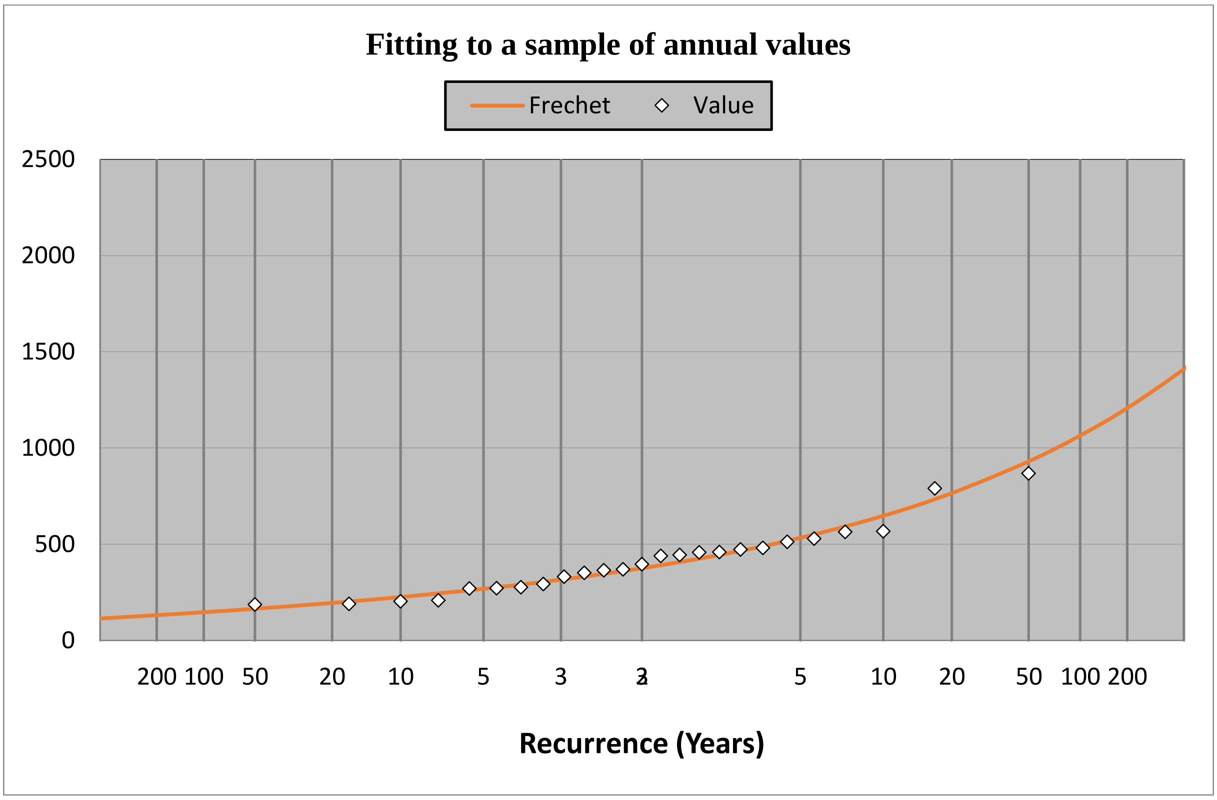



Fitting to a sample of annual values
Gumbel
Value
1800
1600
1400
1200
1000
800
600
400
200
0
200 100 50 20 10 5 3 2 5 10 20 50 100 200
Recurrence (Years)


Fitting to a sample of annual values
Pearson3
Value
1600
1400
1200
1000
800
600
400
200
0
200 100 50 20 10 5 3 2 5 10 20 50 100 200
Recurrence (Years)



Fitting to a sample of annual values
Goodrich
Value
1800
1600
1400
1200
1000
800
600
400
200
0
200 100 50 20 10 5 3 2 5 10 20 50 100 200
Recurrence (Years)



Fitting to a sample of annual values
Frechet
Value
2500
2000
1500
1000
500
0
200 100 50 20 10 5 3 2 5 10 20 50 100 200
Recurrence (Years)

The log normal law appears to be the one fitting the most the data while considering the different plots. Nevertheless, the Bayesian information criterion and the Akaike information criterion results will help in determining which law fit the values the best.

AIC and BIC are based on the maximum likelihood estimates of the model parameters. In maximum likelihood, the idea is to estimate parameters so that, under the model, the probability of the observed data would be as large as possible. The likelihood is this probability, and will always be between 0 and 1. The BIC penalizes models with larger numbers of free parameters. The BIC balances an increase in the likelihood with the number of parameters used to achieve that increase. They are defined as:

$$\boldsymbol{AIC = 2 \times \ln(L) + 2 \times k}$$

$$\boldsymbol{BIC = -2 \times \ln(L) + \ln(n) \times k}$$

Where ln (L) is the log likelihood
k: number of parameters (two in this case: the mean and the variance)
n: size of the sample

3.3.3- Estimation of the log likelihood function

The output sample considered by the normal distribution for instance in Hydraccess is made of n=25 with the mean and the variance respectively equal to $\mu = 411.332$; $\sigma^2 = 28386.677$

The log likelihood function by definition is given by:

$$\boldsymbol{Ln(L)(\mu; \sigma^2, x_1, \dots) = \frac{-n}{2} \times \ln(2\pi) - \frac{n}{2} \times \ln \sigma^2 - \frac{1}{2\sigma^2} \sum_{j=1}^{n} (x_n - \mu)^2}$$

The table below summarise the sample size, the parameters given by the statistical adjustments; and the log likelihood:

Table 5: Log likelihood function of the laws

Statistical laws	n	μ	σ^2	Max. log likelihood
Gauss	25	411.332	28386.677	-163.64
Galton	25	412.112	31384.326	-163.70
Gumbel	25	410.446	28534.484	-163.64
Pearson 3	25	411.332	29568.981	-163.67
Goodrich	25	409.563	34671.266	-163.87
Frechet	25	414.474	35614.842	-163.94

And the Bayesian information criterion and the Aike information criterion gives the results presenting in the table below:

Table 6: BIC and AIC results

Statistical laws	BIC	AIC
Gauss	**333.71**	**331.28**
Galton	333.84	331.40
Gumbel	333.72	331.34
Pearson 3	333.73	331.30
Goodrich	334.18	331.75
Frechet	334.32	331.88

The probability that an event will reflect established beliefs about the event before the arrival of new evidence or information. Prior probabilities are the original probabilities of an outcome. They represent what we originally believed before new evidence is uncovered. New information is used to produce updated probabilities and is a more accurate measure of a potential outcome

3.4- Estimation of the return period

	Return period					
	2	5	10	20	50	100
Frequency	0.5	0.8	0.9	0.95	0.98	0.99
Gumbel	382.7	530.2	630.8	725.6	848.3	940.3
Gauss	**411.3**	**553.1**	**627.3**	**688.5**	**757.4**	**803.3**
Galton	377.56	533.91	641.0	745.9	885.2	992.6
Goodrich	363.0	541.0	662.0	776.0	919.2	1023.2
Pearson III	379.0	538.3	641.9	738.5	859.7	948.1

Table 7: Annual return period results - Fez Saiss Station

The law of Gauss gives the lowest values for the BIC and AIK criterion. In addition, the probabilities of exceedance given by Gauss, reflect what occurred at Fez, considering the historical analysis of the flood events. The law that fit the best is Gauss's law.

What is more, the comparison between the characteristics of the sample (annual rainfall) and the given by Gauss adjustment corroborates the results (Table 8)

Table 8: Law parameters

Parameters	**Sample**	**Gauss**
Mean	411.332	411.332
Median	394.900	411.332
Mode	394.900	411.332
Variance	29569.455	28386.677
Variation coefficient	0.418	0.410
Skewness coefficient	0.970	0.00

3.5- Estimation of time of concentration

The maximum or peak runoff rate from small areas usually results from a rain that covers the area uniformly and lasts long enough so that there is a concentration of runoff from all parts of the watershed. The time required for this accumulation of runoff is called (Tc), the time of concentration. In another word, it is the time it takes for runoff to travel from the most hydraulically distant point in the watershed to a point of interest. Numerous methods exist for estimating time of concentration.

There are various formulas to estimate the time of concentration:

- **Kirpich**

$$T_C = 32.5 \times 10^{-5} \times L^{0.77} \times I^{-0.385}$$

With T_C= Time of concentration (hour)
L= Long twalweg length (m)
I= slope (m/m)

- **Passini**

$$T_C = 0.108 \times \frac{(A \times L)^{1/3}}{I^{1/2}}$$

With T_C= Time of concentration (hr)
A= Area (km2)
L= Twalweg length (m)
I= Slope (m/m)

- **Johnstone & Cross**

$$T_C = 5.66 \times {L/I}^{0.5}$$

With: T_C= Time of concentration (hr)
L= Twalweg length (m)
I= Slope (m/m)

- **Van Te Chow**

$$T_C = 0.123 \times \frac{L}{P^{1/2}}^{0.64}$$

With Tc= Time of concentration (hr)
L= Twalweg length (km)
P= Slope (m/m)

- **U.S. Corps of Engineers**

$$T_C = 0.126 \times \frac{L}{P^{1/4}}^{0.76}$$

With T_C (hr)
L (km)
P (m/m)

- **Californienne**

$$T_C = 0.019395 \times \frac{L}{P^{1/2}}^{0.77}$$

With Tc (minutes)
L (km)
P (m/m)

- **Haspers & Java**

$$T_C = 0.1 \times L^{0.8} \times P^{-0.3}$$

With Tc (hr)
L (km)
P (m/m)

The table below summarise the time of concentration computed with these formula for the watersheds:

Table 9: Estimation of time of concentration

Watersheds	Kirpich	Passini	Jonhstone & Cross	Van Te Chow	US Corps of Eng.	Californienne	Haspers & Java
Boufekrane	0.00029	72.32	176.81	3.24	3.13	3.38	4.19
Mehraz	0.00032	106.14	192.24	3.57	3.49	3.80	4.71
Himmer	0.00033	81.23	180.19	3.59	3.70	3.83	4.88
Smene	0.00012	35.69	127.14	1.56	1.09	1.40	1.52
Chkeff	0.00019	88.96	265.48	2.32	1.27	2.26	2.11
Smene Chkeff	0.00025	86.45	218.07	2.92	2.21	2.98	3.27
Fez	0.00075	307.25	352.64	7.19	7.64	8.82	11.03

It is noticed that Passini and Jonhstone & Cross formula give exaggerated values compared to others formula. The value retained will be the mean of the closed and more logical values aligned with the characteristics of our watersheds.

Table 10: Time of concentration retained

	Formula					
Watersheds	**Kirpich**	Van Te Chow	US Corps of Eng.	Californienne	Haspers & Java	**Retained**
Boufekrane	0.00029	3.24	3.13	3.38	4.19	**3.25**
Mehraz	0.00032	3.57	3.49	3.80	4.71	**3.62**
Himmer	0.00033	3.59	3.70	3.83	4.88	**3.71**
Smene	0.00012	1.56	1.09	1.40	1.52	**1.35**
Chkeff	0.00019	2.32	1.27	2.26	2.11	**1.95**
Smene Chkeff	0.00025	2.92	2.21	2.98	3.27	**2.70**
Fez	0.00075	7.19	7.64	8.82	11.03	**7.88**

3.6- Estimation of peak discharge

In this section, different empirical formula, well adapted to our study area will be used to estimate the peak discharge. These discharges represent the most important properties which will help in characterize the flood hazard risk. Several methods are used to estimate the discharges. For instance, there is the statistical analysis of maximum discharge over a long period of time. Besides that, rational method (Remenieras, 1968) is used in the absence of hydrometric data. This method is based on the runoff coefficient, the watershed surface area and the hourly intensity of the precipitation. However, for our case, it is important to notify that using the rational method will lead us to suppose that the intensity of the precipitation is uniform in the whole watershed for the whole duration of the rainfall. Due to those constraints, the empirical formula used (since there is lack of some hydrologic data) will be based on different geometric characteristics of the watersheds.

Presentation of the formula used in the Moroccan context

- **Mallet Gauthier Formula**

$$Q(T) = 2 \times K \times Log_{10}(1 + aH) \times \frac{A}{\sqrt{L}} \times \sqrt{1 + 4Log(T) - Log_{10}(A)}$$

Q (T): Peak discharge (m^3/s)
K: Coefficient 0.50 (low slope), 5.0 (high slope)
a: Influence coefficient between 20 – 30
H: Mean height of rainfall
L: Talweg length (km)
T: return period
A: Surface Area (km^2)

Achite et al., (2006) explains that this formula is used in some Maghreb countries like Algeria, Tunisia and Morocco; to estimate the peak discharges for different return period.

Hazan – Lazaveric formula

$$Q_T(1000) = K_1 \times S^{K_2}$$

$$Q_T(10) = Q_{1000} \times \frac{1 + a \times Log10}{1 + a \times Log1000}$$

With Q_T (1000): peak discharge (m^3/s) of 1000 years recurrence
Q_T (10): peak discharge (m^3/s) with a return period of 10 years
a: coefficient varying between 0.8 and 1.2 depending on the permeability of the watershed
S: surface area of the watershed (km^2)
K_1 & K_2: factors depending on pluviometry and geographical localisation of the watersheds (Table 10).

This formula is deduced form information gathered within different Moroccan watersheds. The millennial discharge is a function of the watershed surface area. The formula suits all the Moroccan watersheds.

Table 11: K1 and K2 values depending on location and pluviometry in Morocco
Source: (ABHS, 2010)

Factors	Central Rif	Western Rif	Eastern Rif	Middle Atlas		
P (mm)	1000 - 1300	800 - 1000	600 - 800	700 - 900	500 - 700	400 - 500
K_1	15.55	9.78	7.58	14.94	13.51	13.47
K_2	0.776	0.793	0.808	0.636	0.613	0.587

Fuller II formula

$$Q(T) = [1 + a \times Log(T)] \times \left[S^{0.8} + (8/3)S^{05}\right] \times \frac{4}{3} \times \frac{N}{10}$$

Q(T): Peak discharge (m^3/s)
T: Return period
a: coefficient 07 to 0.8 according to the permeability and the slope of the watershed
A: Surface area (km^2)
L: Talweg length (km)
N: Regional coefficient 80 in the plain domain, 85 in terrain between plain and mountains, 100 in the mountains

The peak discharges have been computed for the return period of 10, 50 and 100 years. In prior to the results, the following table summarize the geometric characteristics and the regional coefficients of the watersheds.

Table 12: Regional coefficient of the watersheds

Watersheds	Area	Perimeter	Talweg length	Slope		Pan	Coefficients				Outlet coordinates		
	Km^2	km	km	%	m/m	mm	K	K_1	K_2	N	x	y	z
Boufekrane	52.40	63.14	28.3	2.87	0.029	470	1.1	13.47	0.587	85	539021	384117	300
Mehraz	137.70	75.71	32.3	2.81	0.028	490	1.1	13.47	0.587	80	538928	384148	300
Himmer	80.74	80.03	37.5	3.68	0.037	500	1.4	13.51	0.613	85	533113	382954	377
Fez	878.77	206.46	85.4	2.18	0.022	550	1	13.51	0.613	80	543614	386783	187

The results obtained after estimation are presented and discussed in the Chapter V.

Chapter IV: Hydraulic modeling

Hydraulic model development

Oued Mehraz modeling approach

Oued Boufekrane modeling approach

4.1- Hydraulic model development

This section provides a detailed description of the methodology that was applied to obtain the hydraulic modeling results. The main objective of the hydraulic model was to estimate the flood hazard of the fez watershed with return periods of 10, 50 and 100 years in the Boufekrane and Mehraz stream. In order to obtain results that could be incorporated into a flood hazard map, hydraulic models with different cross section configurations and additional geometric features were developed with HEC-GeoRAS and analysed regarding the validity and accuracy of the simulation results. The final modeling approach that was developed based on the preliminary simulations is described in the following section. In prior to that this schematic outlines the methodology:

4.1.1- Oued Mehraz modeling approach

The final hydraulic model was primarily used to define the locations of the channel, where bank overtopping can be expected to occur after a certain threshold flood discharge is exceeded. The chart below describes in detail the means used within the ArcGIS environment, HEC-GeoRAS and HEC-RAS:

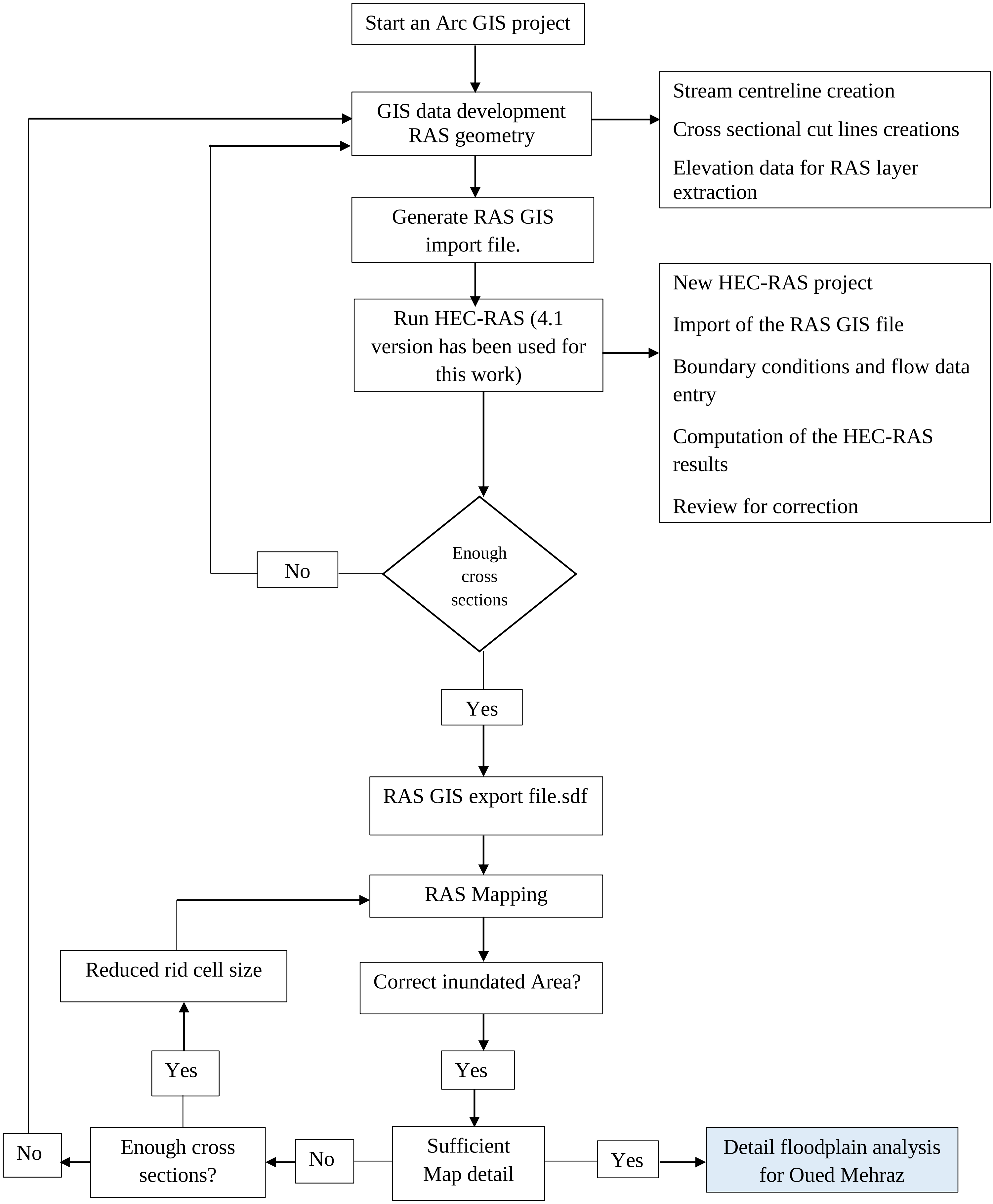


Figure 23: Oued Mehraz hydraulic modeling process
Adapted from HEC (2009)

4.1.2- Model Creation Geometry within HEC-GeoRAS

4.1.2.1- GIS data and RAS geometry

Based on the topographic datasets the HEC-RAS model geometry file was developed using HEC-GeoRAS in conjunction with ArcMap. The data requirements for the geometric model in HEC-RAS are described in detail in Chapter I. The methodology used for the creation of the geometric model in HEC-GeoRAS is presented in the following sections.

4.1.2.2- Cross Section expanding and extend

Since the cross sections built the computational nodes for the water surface profile calculations, their configuration as defined in HEC-GeoRAS directly influences the modeling results. The HEC-RAS Hydraulic Reference Manual provides the following general guidelines for the placement of the cross sectional cut lines along a reach (HEC, 2010b):

- Cross sections are required at representative locations along the modeled reach and at locations where changes occur in discharge, slope, shape or roughness.
- Cross sections should span across the flow channel and the entire floodplains.
- At locations where abrupt changes occur in the channel geometry, cross sections should be placed close enough to describe the changes accurately.
- Cross sections should be placed perpendicular to the expected flow paths in the channel as well as in the left and right overbanks.

In the modeling process, each cross section is assumed to be representative for the reach geometry half way to the next up- and downstream cross section. The appropriate spacing of the cross sectional cut lines along the modeled reach depends on the channel size and slope as well as on the uniformity of the cross section shape. Since the spacing of the cross sections directly influences the stability and accuracy of the modeling solution, equations have been developed in order to estimate the maximum cross section spacing as a function of different channel parameters. HEC (2010b) suggest using Eq. 5.1 which defines the maximum distance between cross sections based on the average bank full depth of the main channel (D) and the average channel bed slope *So.*

The figure below sheds light on the geometry data obtained within HEC-GeoRAS on Mehraz stream.

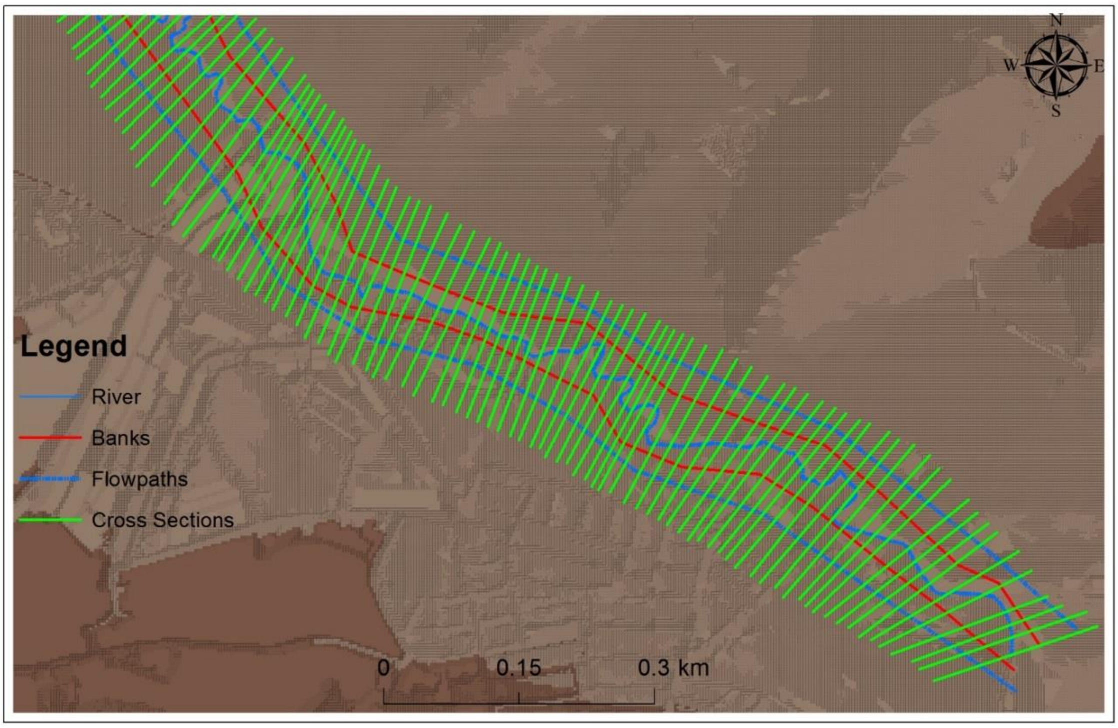


Figure 24: Oued Mehraz RAS geometry within HEC-GeoRAS

4.1.3- File import to HEC-RAS 4.1

4.1.4-Flow data and boundary Conditions

The type of flow data entered depends upon the type of analysis to be performed in the project. In present paper, the steady flow analysis is performed. It has been assumed that Mehraz flow does not change with time.

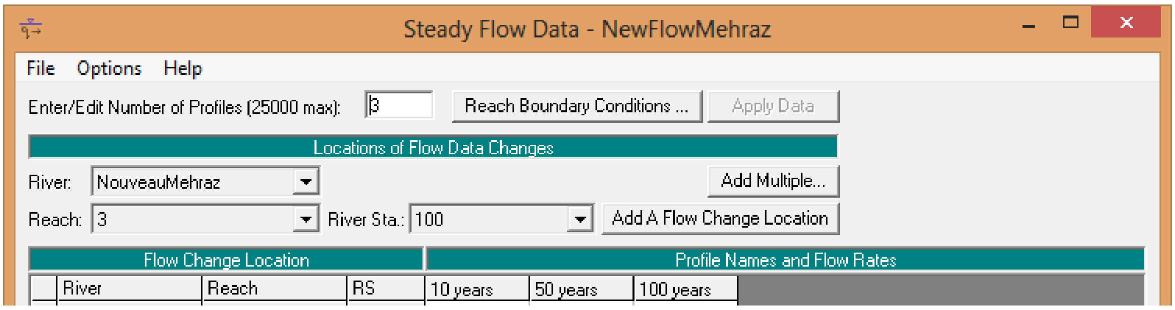


Figure 25: Oued Mehraz Flow data - HEC-RAS

The boundary condition used in this work is the normal depth assumption. Actually, it has been assumed that oued Mehraz flows under normal or uniform flow conditions at the downstream boundary of the model. That allows to provide the energy slope for all profiles. The normal depth assumption has been chosen for the boundary conditions due to its ease of use and its semi dynamic properties. As a matter of fact, as the flow changes, so will the downstream boundary depth.

However, using the normal depth slope as boundary conditions; leads to question about what slope to use. With respect to Manning equation, the most effective answer is the discrete energy slope at the downstream cross section. It then has to be computed and to do so an energy slope needs to be assumed. This work assumes an energy slope for the downstream boundary by measuring the average bed slope for oued Mehraz in the profile plot in HEC-RAS. A dx/dy is obtained and that is the slope of the stream. Another method used for comparison is the measurement of the bed slope of the last two cross sections at the downstream boundary.

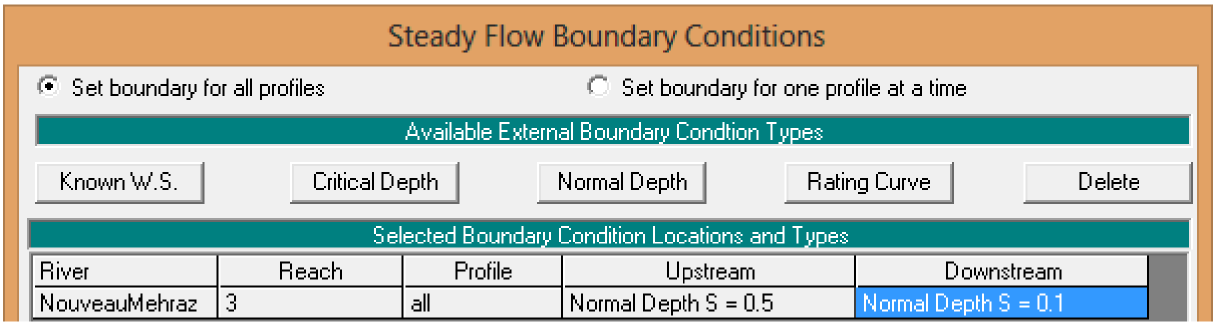


Figure 26: Oued Mehraz Boundary Conditions: normal depth

After Flow and boundary conditions data have been entered, RAS performed a steady flow simulation for a super critical flow. The work proceeds in RAS mapper for the floodplain mapping for the profiles considered (10, 50 and 100 years). After verification, the results are post treated in ArcGIS.

4.1.5- Oued Boufekrane Modeling

The chart below presents the process followed for oued Boufekrane modeling:

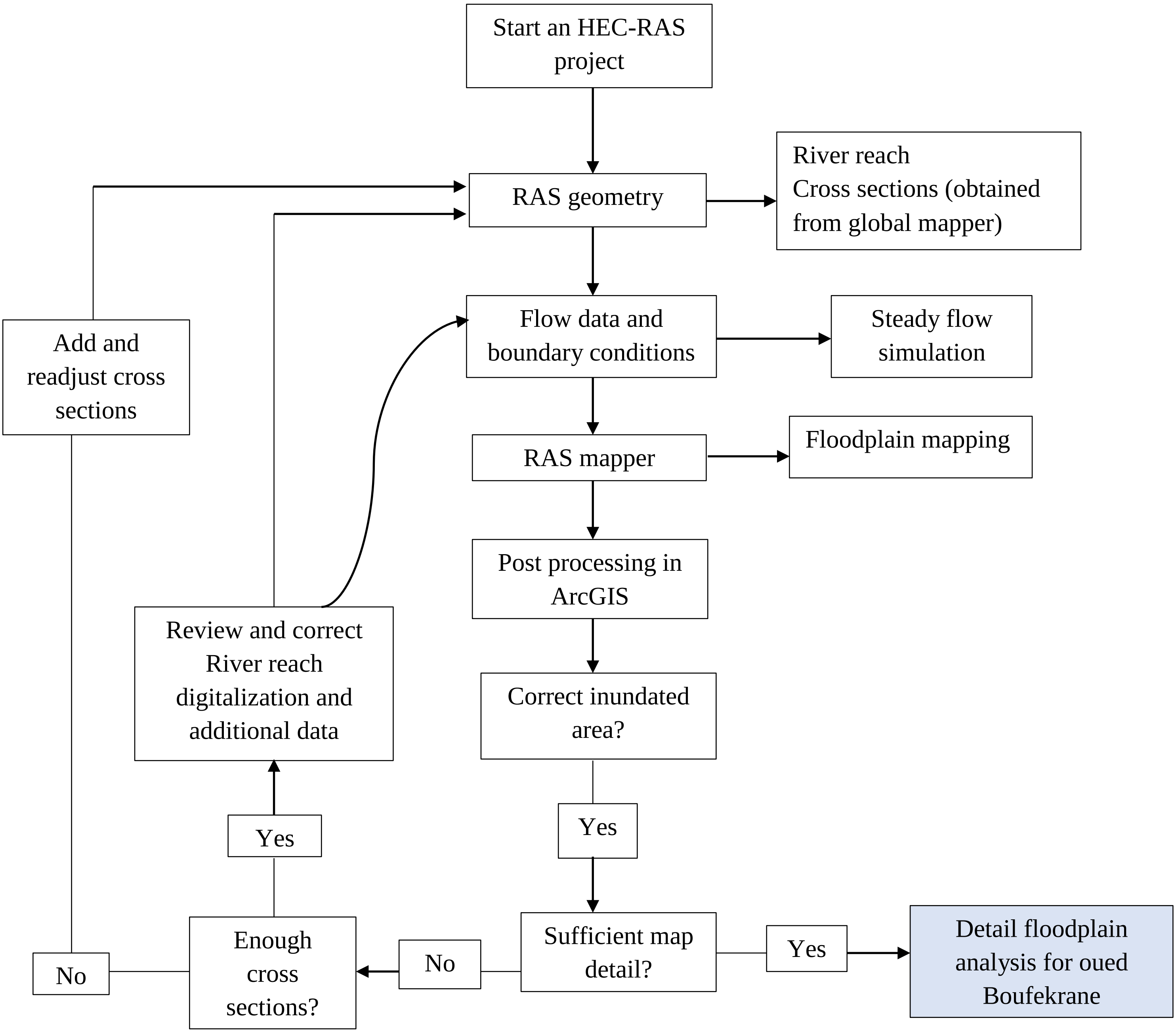


Figure 27: Boufekrane hydraulic modeling process using HEC-RAS

4.1.5.1- Geometry of the project for Oued Boufekrane

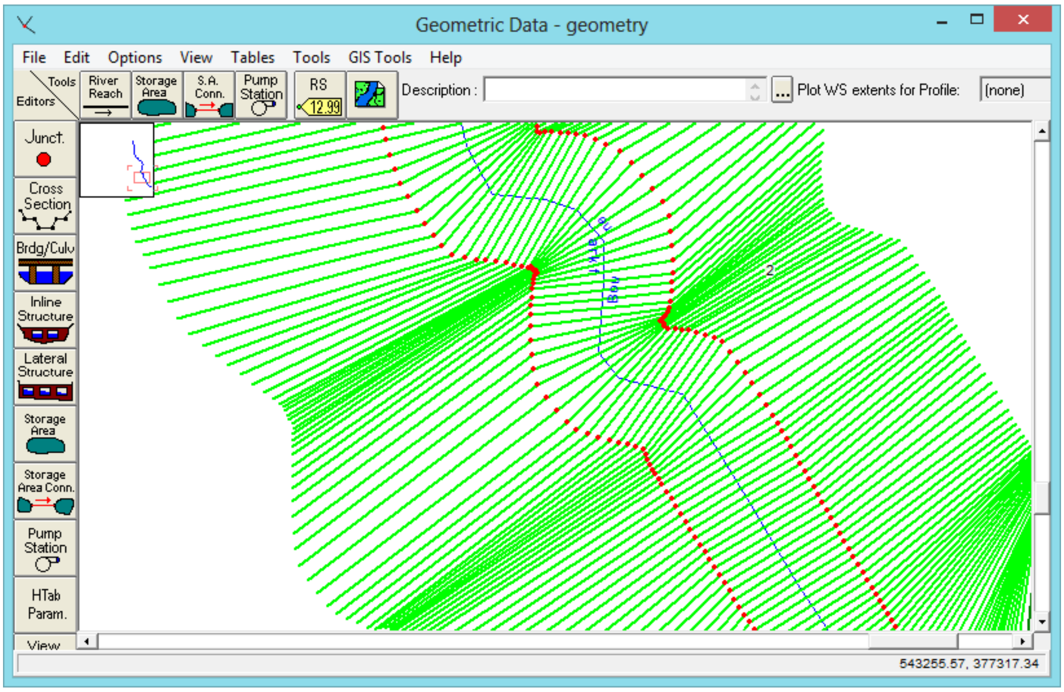


Figure 28: Geometry creation for Oued Boufekrane in HEC-RAS

Perform a steady
flow simulation

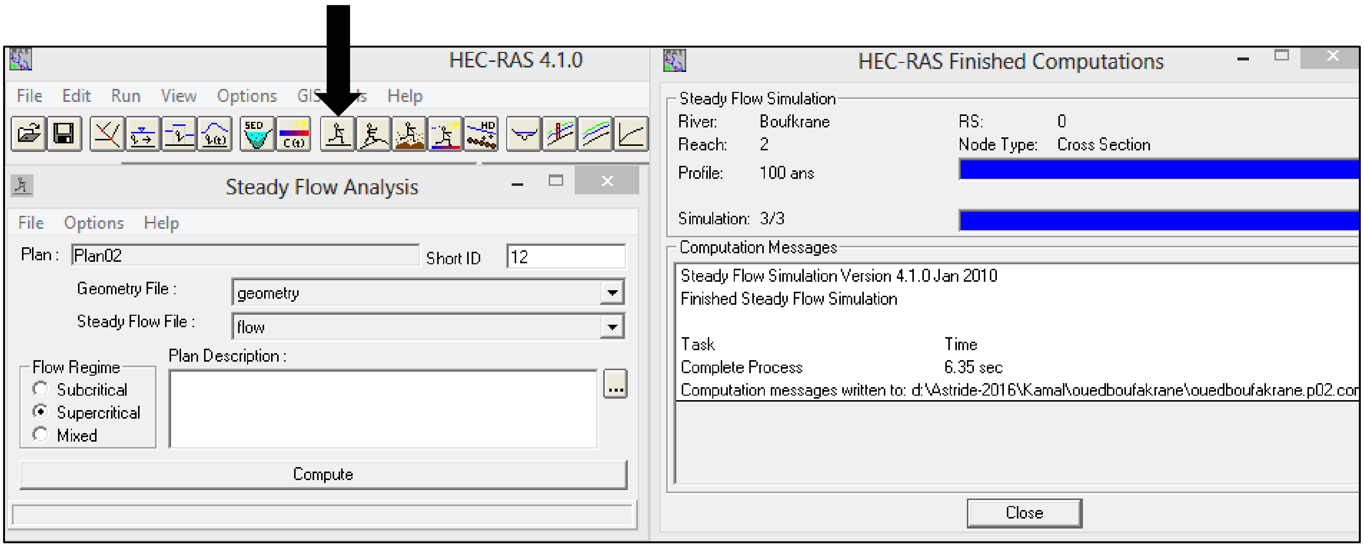


Figure 29: Simulation Step in HEC-RAS

Chapter V: Results and discussion

Hydrologic response of the watersheds results

Hydraulic modeling results

Floodplain mapping

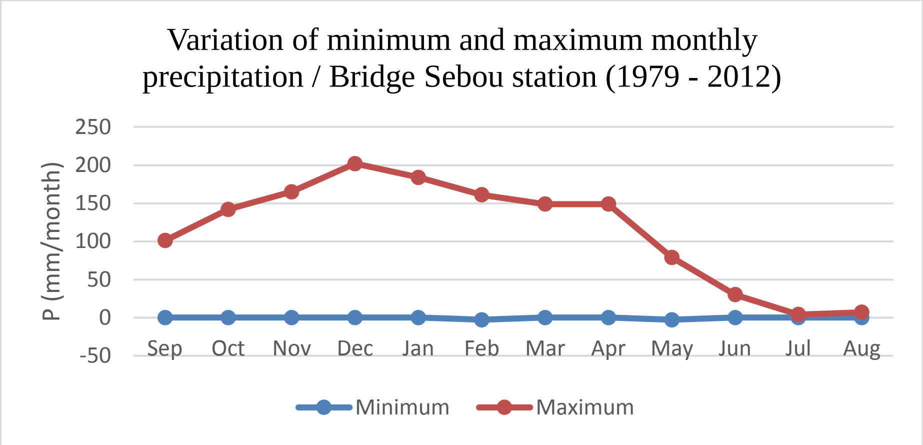
In this chapter, the hydrologic response of the watershed analysis and the hydraulic modeling results as well as the flood hazard mapping are presented. The accuracy of the hydraulic modeling results is validated in the frame of a sensitivity analysis. The flood hazard mapping is based on the results obtained from the hydraulic modeling and a detail analysis of the morphology of the study area.

Photo 9: Oued Fez water stream
Taken in June 2016

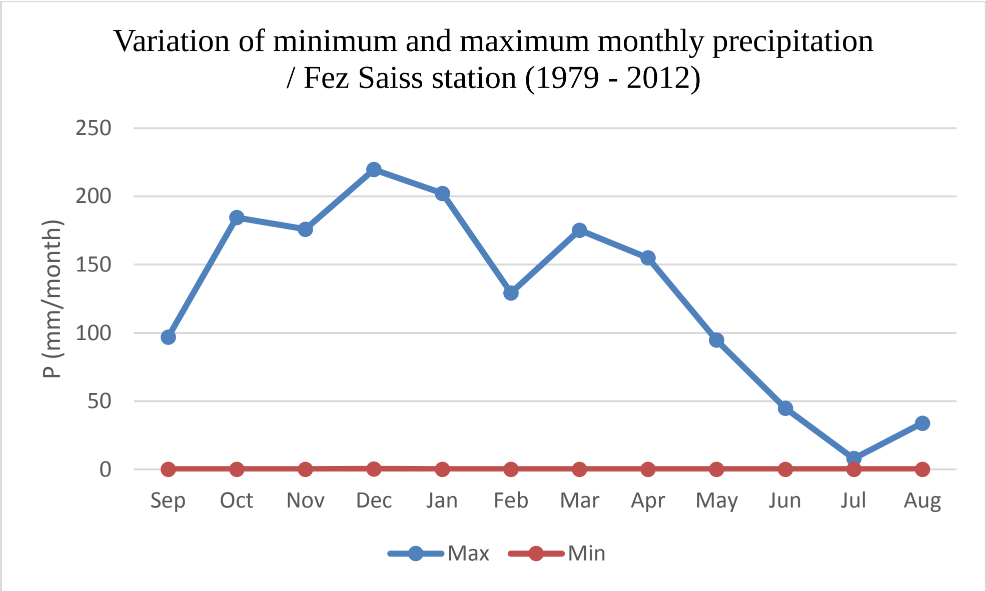
5.1- Hydrologic response of the watersheds

According to the results obtained, it is clear the watersheds can generate exceptional flood, considering the analysis of the historical flood events, before and after the construction of some hydraulic structures. For instance, the water depth can be 49 mm in only 12 hrs, as it was the case in Ain Bettit Station in 1989 and most importantly in Fez, there is no need of rainfall before a flooding event as it was the case in September 2008 where the city has been flooded due to rainfall events occurred in some of its watersheds. It is then obvious that the position of the city influence greatly the hydrological response of its watersheds; because it is located in the confluence zone of the whole hydrographic network of the basin.

Besides that, the analysis of the rainfall data from 1979 to 2012, shows a maximum annual rainfall of 555 mm/year with a minimum of 0 mmm/year. In addition, there is a great variation between the maximum and the minimum monthly rainfall as shown in the graphs below in two different stations, meaning that from 0 mm, there can be a sudden rainfall event greater than 50 mm in a day within a short period of time or not; but causing a considerable amount of runoff.

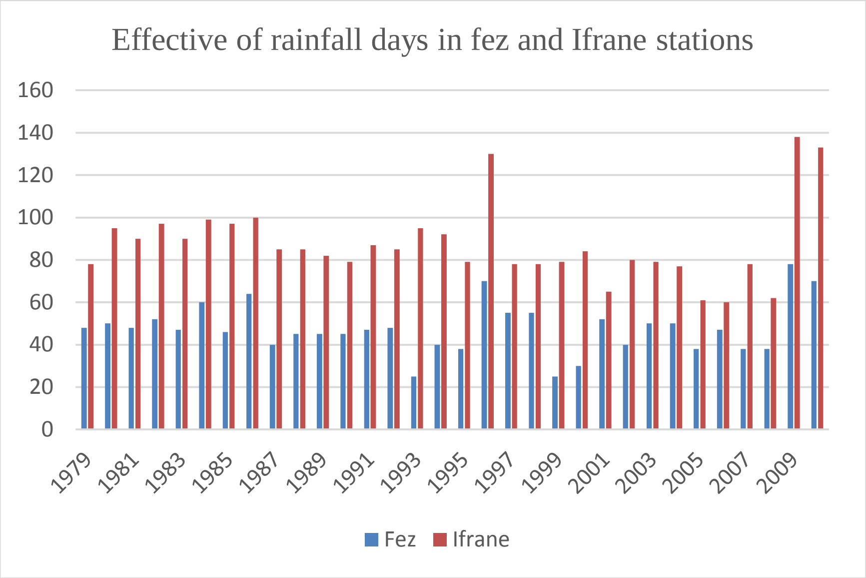


Graph 12: Variation of minimum and maximum monthly precipitation / Bridge Sebou (1979 - 2012)



Graph 13: Variation of maximum and minimum monthly precipitation / Fez Saiss station (1979 - 2012)

In addition, while comparing the annual variation of the precipitation with the effective number of rainfall days, a high correlation is noted between the two, in a sense that the humid years correspond to where there is a maximum of rainfall days. Then to the contrary, the dry years recorded the low number of precipitation days. However, the disparity between the numbers of days in two different stations (graph 14) gives also an appreciation on how irregular the pluviometry regime is within the watershed.



Graph 14: Effective of rainfall days in Fez and Ifrane stations

Besides that, time of concentration is a fundamental watershed parameter. It is used to compute the peak discharge for a watershed. The peak discharge is a function of the rainfall intensity, which is based on the time of concentration. Time of concentration is the longest time required for a particle to travel from the watershed divide to the watershed outlet. According to the different time of concentration obtained, it is relevant to notice that they are relatively short; except Oued fez outlet. That implies that there is a relatively fast runoff within the watersheds.

Table 13: Time of concentration in hour: minutes

Watersheds	Boufekrane	Mehraz	Himmer	Smen	Chkeff	Smen Chkeff	Fez
Tc retained (h:minutes)	**3h:15**	**3h:37**	**3h:42**	**1h:21**	**1h:57**	**2h:42**	**7h:52**

Furthermore, peak discharges represent also one of the most important hydrologic parameter to evaluate the flood hazard. They have estimated based on different empirical formula and the results are presented below:

Table 14: Peak discharges (m^3/s)

Watersheds	**Peak discharges (m^3/s)**								
	Mallet Gauthier			Hazen - Lazaveric			Fuller II		
	10	50	100	10	50	100	10	50	100
Boufekrane	116	133	153	72	77	82	120	142	172

Mehraz	321	375	462	112	128	149	230	273	330
Himmer	152	176	202	107	117	126	160	190	229
Fez watershed	1060	1299	1503	457	472	530	851	1009	1218

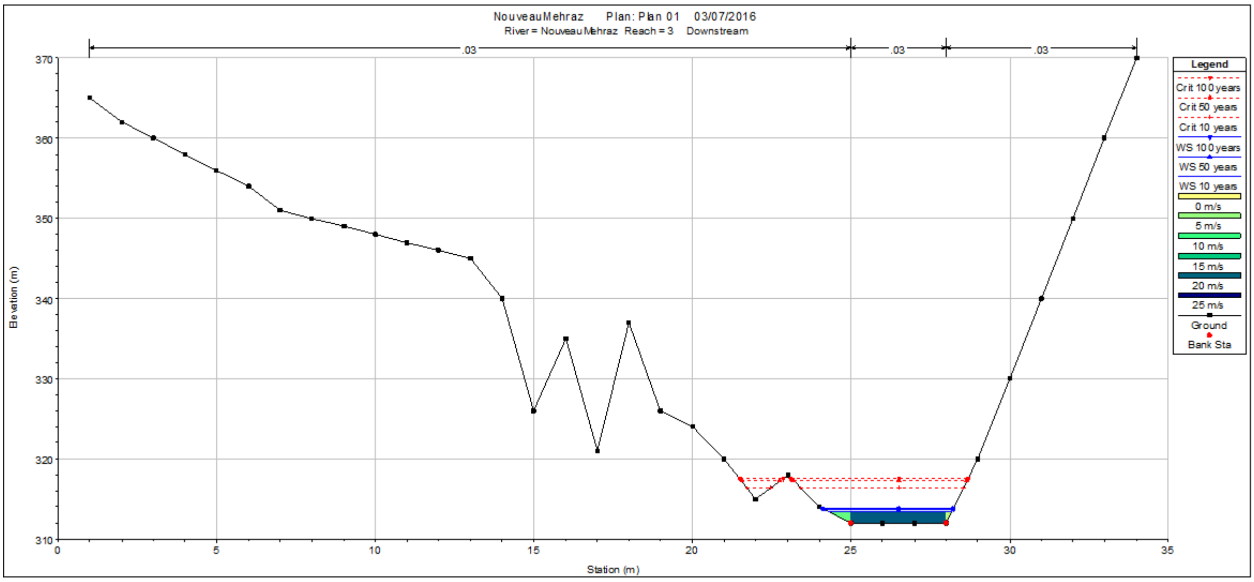
The results present a disparity between the three methods. Hazan-Lazaveric gives low values comparing to the two others which gives approximately closed values. Nevertheless, it is important to precise that peak discharges estimated with the three different formula give high values especially for the centennial flood. Mallet – Gauthier and Fuller II estimation gives peak discharges approximately closed to the discharges observed during some historical floods events.

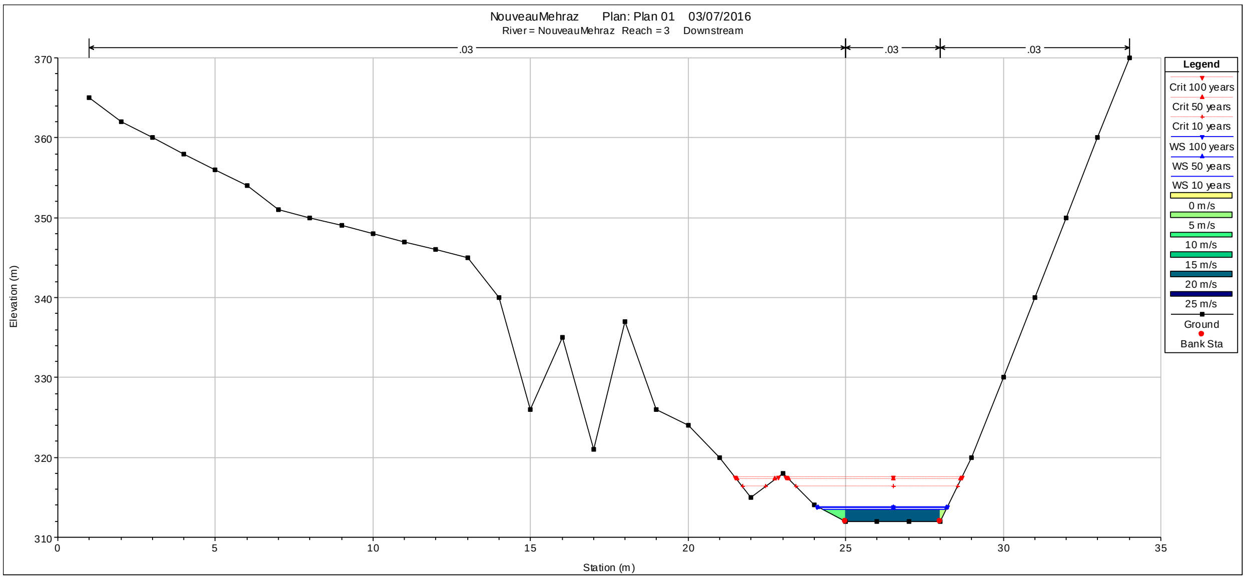
These peak discharges estimation represent a veritable danger for the population and for the city of Fez. For instance, Oued Mehraz centennial flood has been estimated as 452 m^3/s, but in 1950, it exceeded and reach 500 m^3/s. Even though the frequency of those kind of events are rare, it is crucial to point out that the damages they can occasion are extremely costly in terms of life and properties.

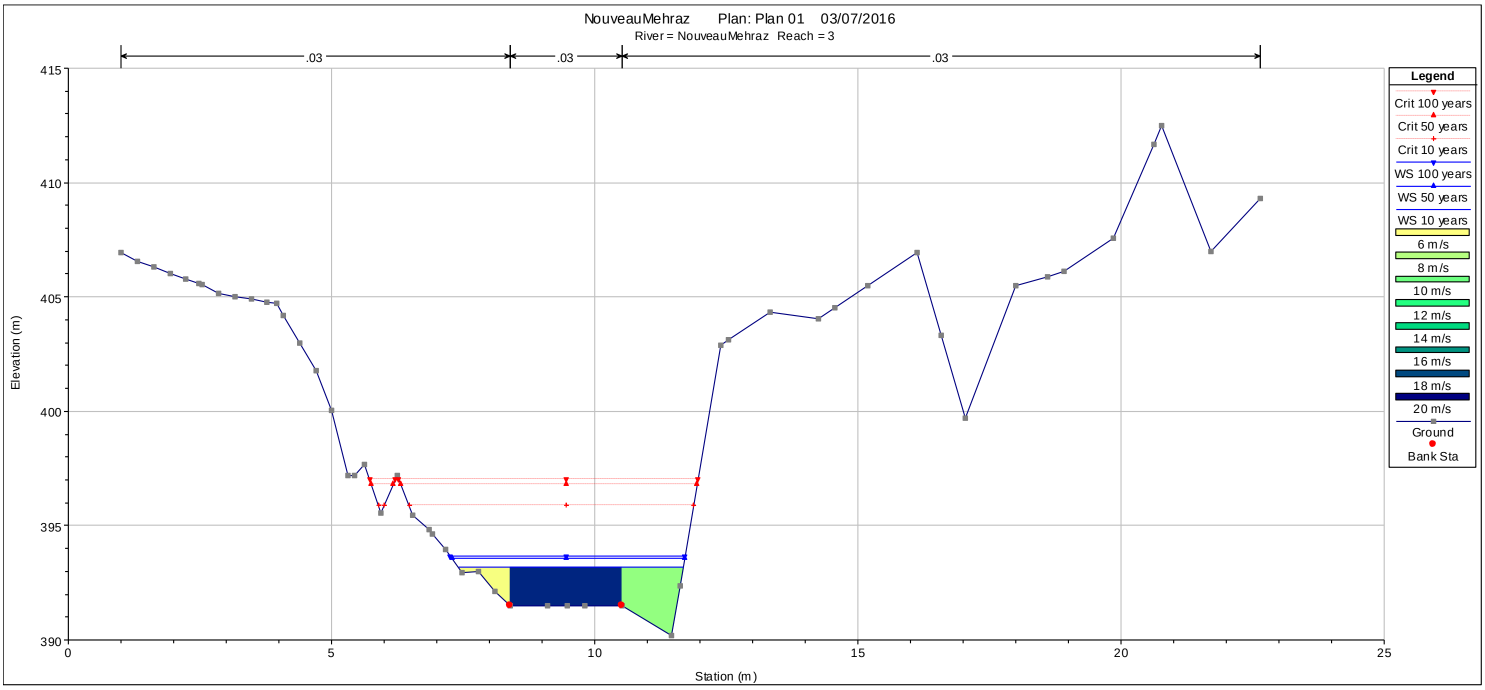
The next part will present and discuss the results obtained from the hydraulic modeling using ArcGIS, HEC-GeoRAS and HEC-RAS.

5.2- Hydraulic modeling result

The hydraulic modeling performed in HEC-RAS has allowed the simulation of the water levels, the velocity and the areas submersible by the decennial, the 50- years and the 100- years flood. The results are presented below.




NouveauMehraz Plan: Plan 01 03/07/2016
River = NouveauMehraz Reach = 3 Downstream
.03
.03
.03
Legend
Crit 100 years
Crit 50 years
Crit 10 years
WS 100 years
WS 50 years
WS 10 years
0 m/s
5 m/s
10 m/s
15 m/s
20 m/s
25 m/s
Ground
Bank Sta
Elevation (m)
Station (m)


NouveauMehraz Plan: Plan 01 03/07/2016
River = NouveauMehraz Reach = 3
.03
.03
.03
Legend
Crit 100 years
Crit 50 years
Crit 10 years
WS 100 years
WS 50 years
WS 10 years
6 m/s
8 m/s
10 m/s
12 m/s
14 m/s
16 m/s
18 m/s
20 m/s
Ground
Bank Sta
Elevation (m)
Station (m)

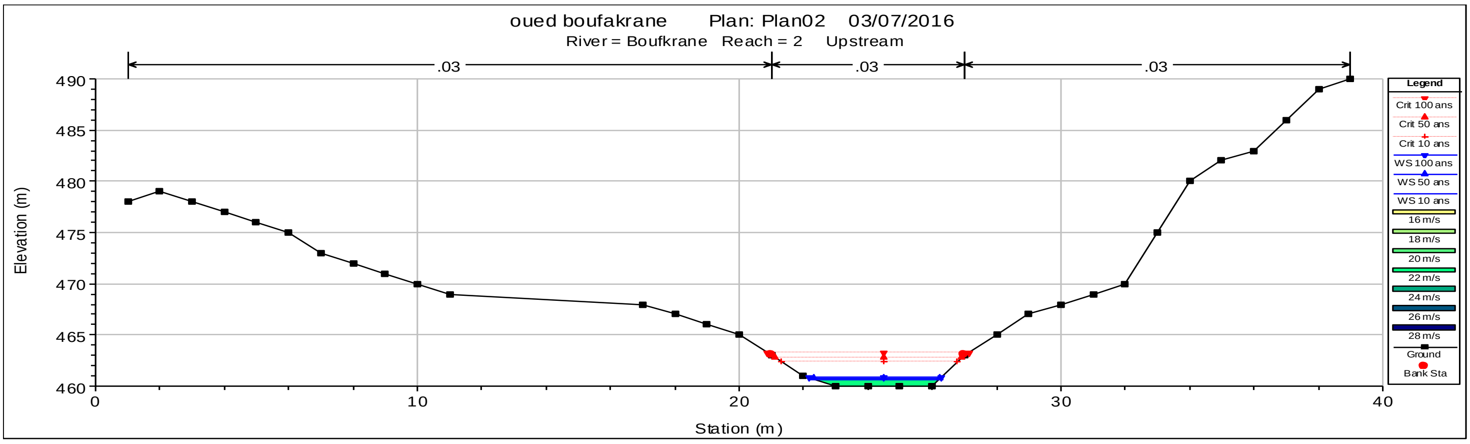


Figure 30: Profile plot for the streams

The flood hazard maps are presented below for Oued Mehraz and Oued Boufekrane respectively :

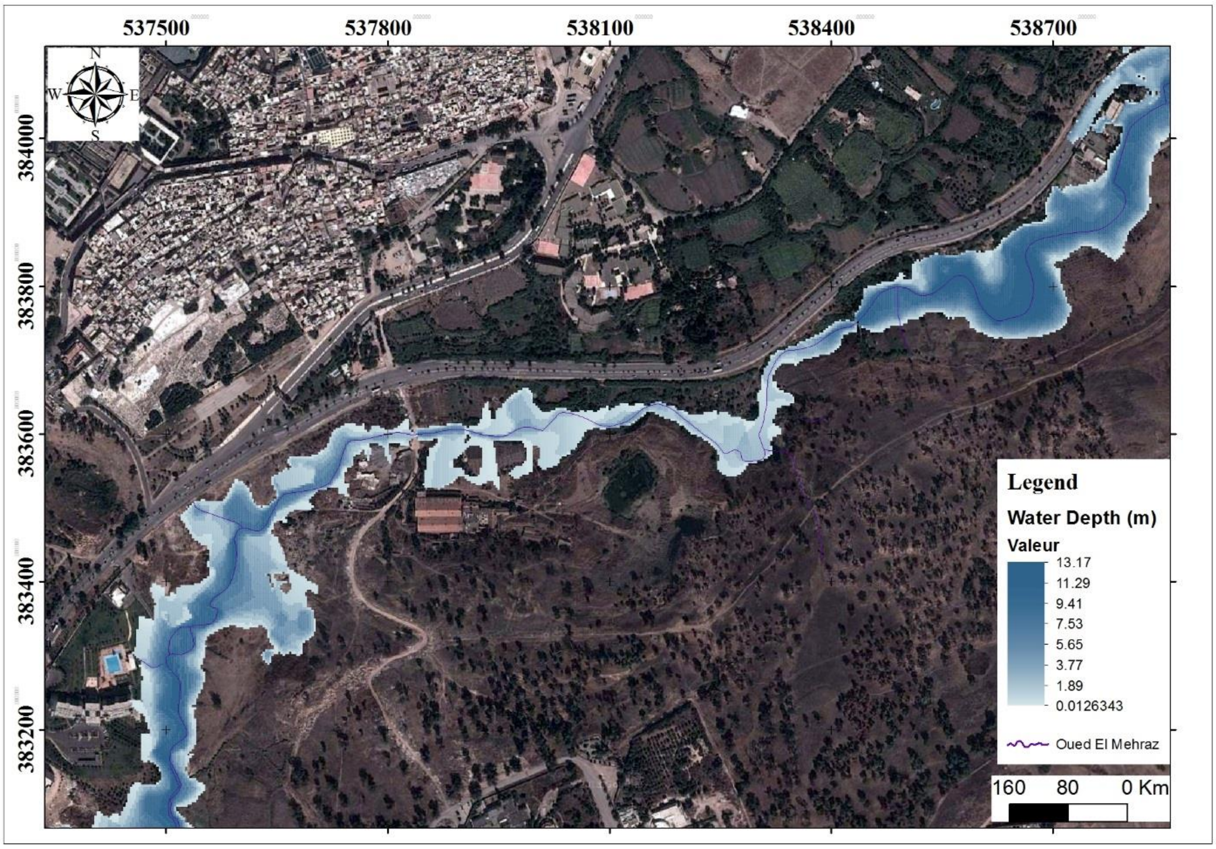


Figure 31: Oued El Mehraz 10 years flood water depth (m)

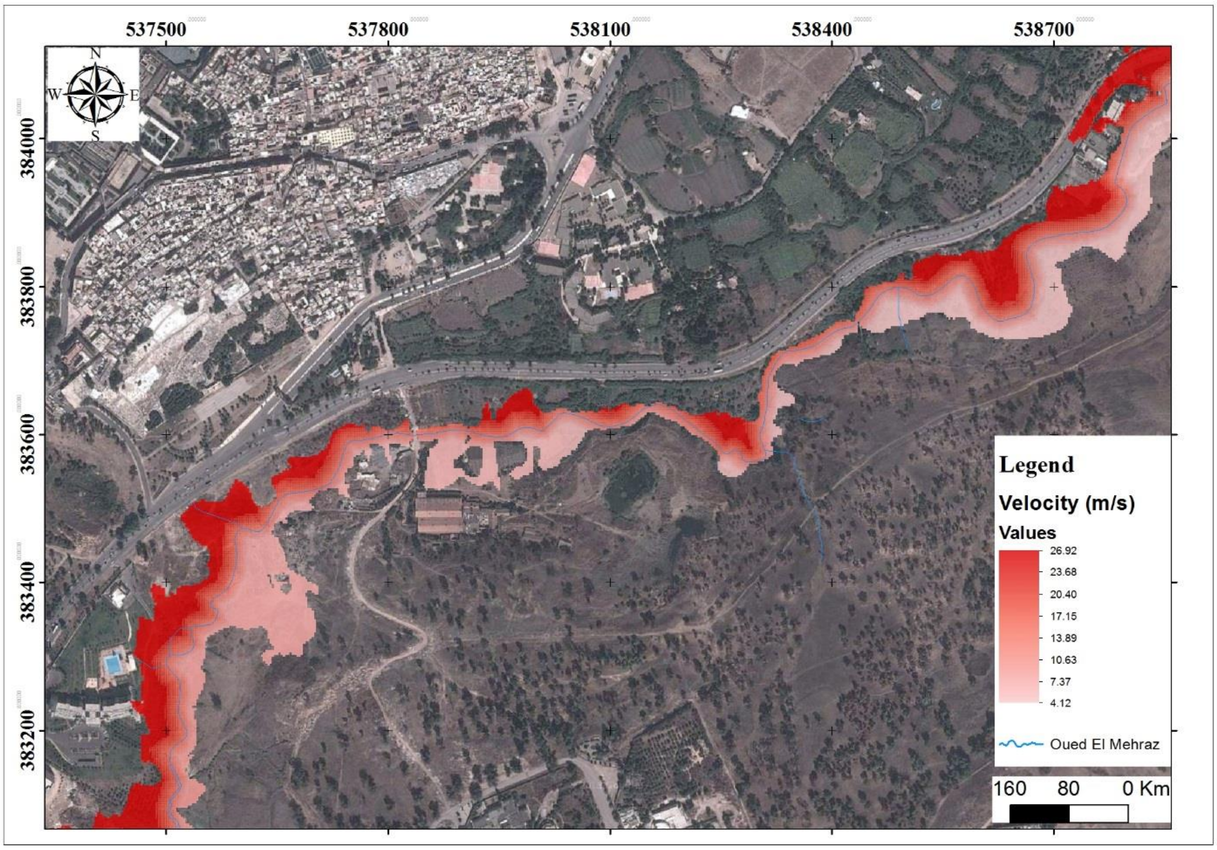


Figure 32: Oued El Mehraz 10 years flood velocity (m/s)

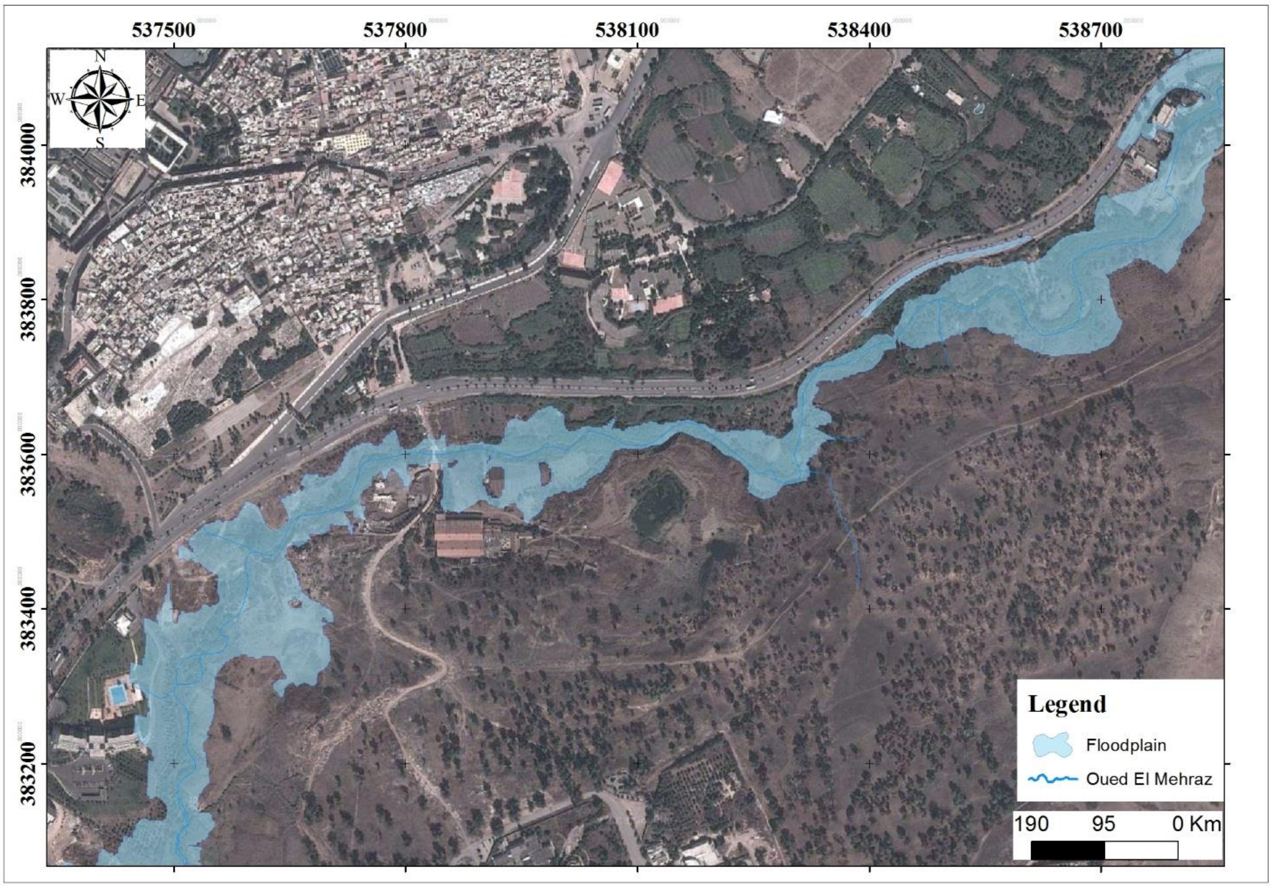
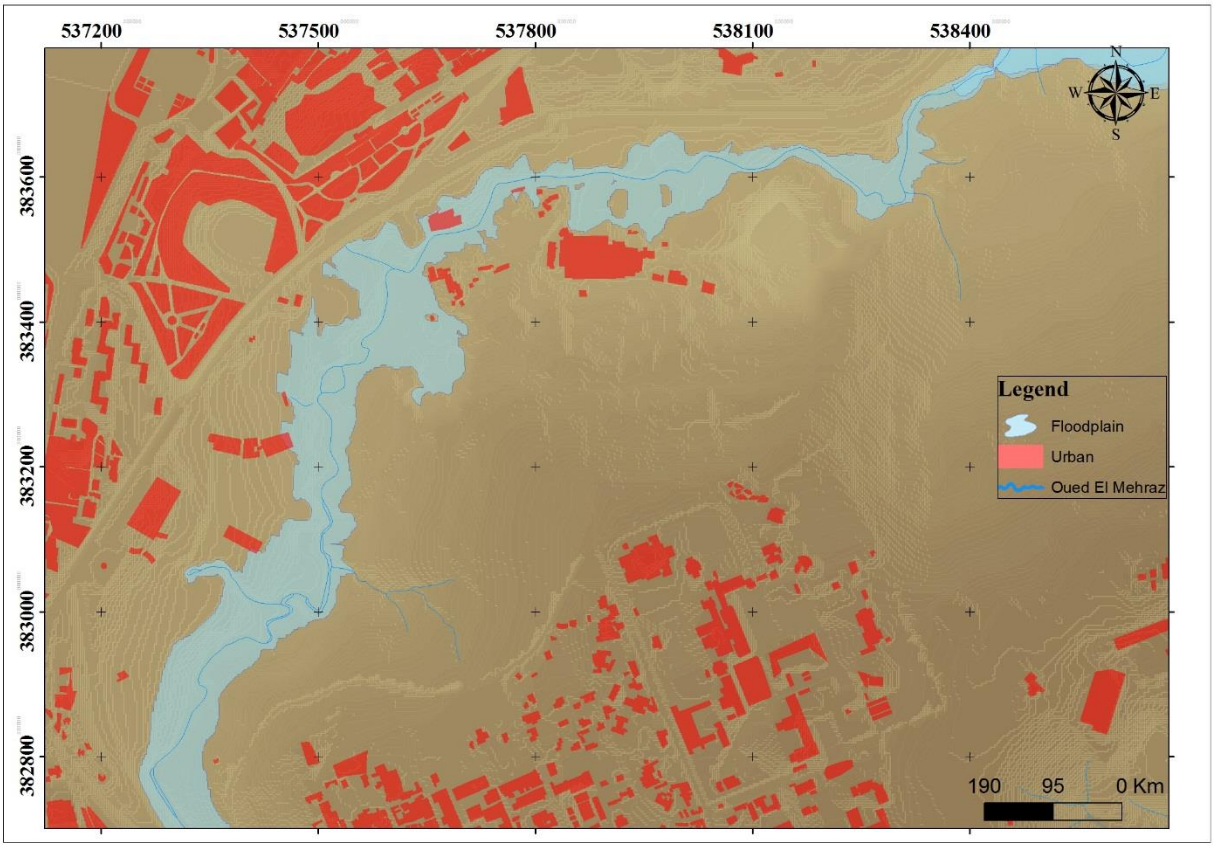


Figure 33: Floodplain Oued El Mehraz (100 years)



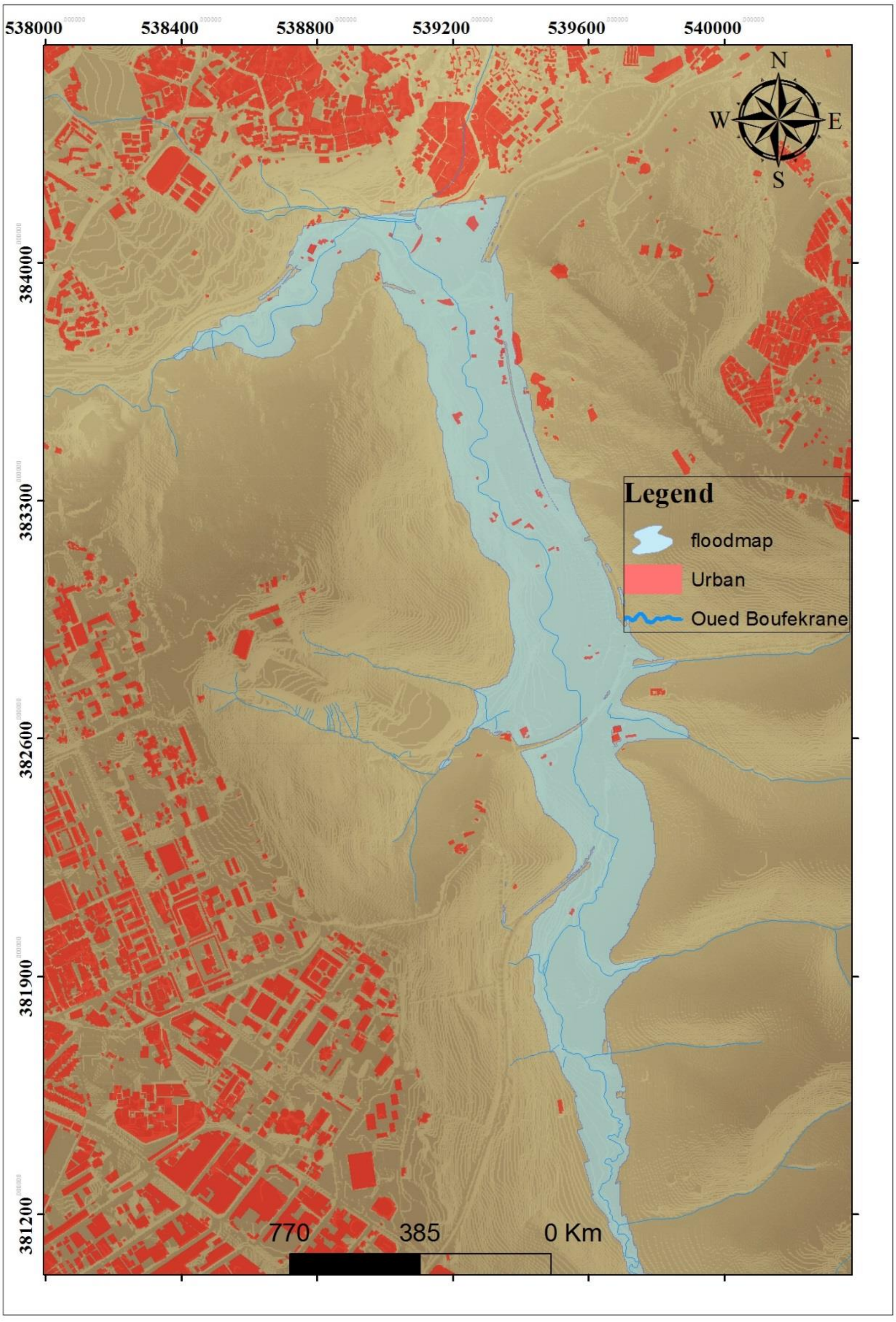


Figure 34: Oued Boufekrane floodplain map (10 years)

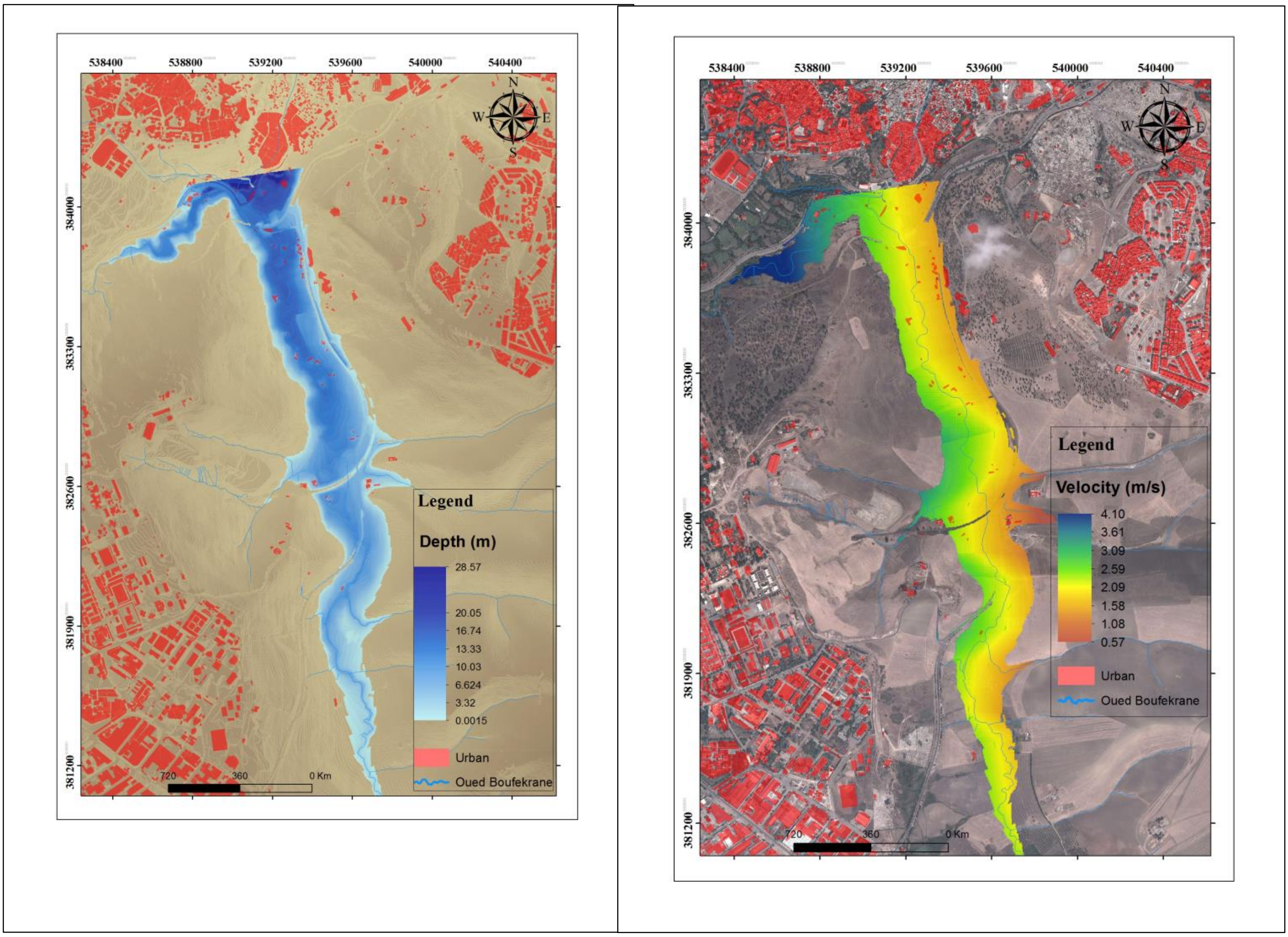


Figure 35: Depth and Velocity Oued Boufekrane (10 years)

The flood depth map provides information about the water depth in a particular location for a given recurrence interval (or probability) of flood. Here, the results are given in meters (m). Oued Boufekrane has a hollow valley restricting its lateral overflow which generally do not exceed 70 meters. Actually the flooding generated by oued Boufekrane take the path of the entrance of the medina where the waters flow at a velocity exceeding 4m/s. The water depth can reach and exceed 25 m. That represents a high hazard. In addition, as it was for the September 2008 event, the overflow of El Gaada dam occasioned Aouinat El Hajjaj district flooding.Oued Mehraz occasion severe inundations illustrating by the 1950 flooding where the peak discharge estimated, reach 500 m^3/s.

General Conclusion and Recommendations

The Kingdom of Morocco in general and its Fez agglomeration in particular is characterized by a high variation of hydrological or rainfall events, which is exacerbated by the global change in the climate. The water basins of the agglomeration accelerate the irregularity of the runoff due to their topographic, geologic, morphometric and anthropogenic factors, which finally make the meteorological events extreme, increasing the hydrological hazard; in addition to the uncontrolled urban development, which increase the vulnerability and therefore the risk. That flooding risk in Fez is fostered by the position of Fez city within the confluence zone of the whole hydrographic network of the watershed.

The major goal this study was to reach is to undertake a flood modeling based on Geographical Information System (Arc-GIS) and HEC-RAS. The database of the GIS maps provides people, related agencies and organisations with a better view of the real situation. It serves as a guide map for stakeholders working in the study areas to implement disaster risk reduction projects and programmes. Furthermore, by distinguishing between areas that are safe and those that are vulnerable to natural disasters, it is easier to ensure that emergency plans for evacuation or preparedness are developed properly.

What is more, flood maps are used by many different stakeholders. The maps serve at least one of the three purposes of flood risk management:
(i) prevent the build-up of new risks (planning and construction),
(ii) reduce existing risks, and
(iii) adapt to changing risks factors

Besides that, it is important to notify that before the hydraulic modeling, this report analyses the factor affecting the flood risk in oued Fez watershed in addition to the different behaviour of its watersheds. What is more, the study performed a frequency analysis of the historical rainfall events as well as the hydrological response of the watershed.

With respect to the hydrological analysis of the watersheds, the morphometric and physiographic characteristics of the watershed denote a soft hydrological response. However, based on the analysis of the intensity of the rainfall events, it appears that the watersheds can generate exceptional flooding which are evidenced by the historical flooding events in Fez city. The peak discharges estimated by the empirical formula also are important and can generate catastrophic damages in the future. This vulnerability induced by the hydrological hazard in Fez city is alarming.

The following recommendations could help in minimizing the flooding risk in Fez agglomeration:

- Cleaning and emptying the drainage canal at the end of summer or the dry season at least
- Increase the dams' reservoirs capacity and ensure their good maintenance to avoid their filling or invasion.
- Ensure a good management of solid wastes to avoid the filling or the eutrophication of the oueds.
- Create natural water retention by the realisation of green space surrounding the oueds
- Undertake the recalibration of the oueds El Himmer and Ain Smen to create a boundary and avoid overflow induced by frequent flooding.
- Infiltration techniques

Moreover, Flood mapping heavily depends on data. Depending on the methods and techniques chosen, the need for accurate data is high. The task is not easy with some absence of data. Some recommendations are expressed here to make that effortless:

- Elaboration of high resolution of DEM

These tools are nowadays significant for a hydrological and geomorphological analysis of a watershed. They constitute a useful implement for modeling. The authorities in collaboration with competent educational institutions (university of Fez for instance) could produce those DEM especially in urban area where the vulnerability and the risk are considerable.

- Production of a climatic, hydrologic and geologic database

These type of data are extremely useful for hydrological modeling and forecasting. It could be judicious to centralize the data (discharges, rainfall, class and type of soils…) at a watershed scale and make them available for work, study and research purpose.

- Enhance the accuracy and increase the location of hydrologic and climatic measurements

The different stations of measurements need to be diverse and effective in order to ensure a better spatial and temporal homogeneity of the precipitation. It would also be beneficial to increase the number of the stations, especially in the rural areas where they are just fewer.

- Enhance and frequently update the flood hazard mapping

It is crucial to integrate local knowledge, GIS and maps into the process of disaster risk management. There are three main reasons for this integration: (i) a hazard map plays a key role in disaster risk identification, and it is an effective tool in making local knowledge visible; (ii) local knowledge is essential for disaster risk management; and (iii) GIS maps have advantages over conventional maps, the reason underlying the value of maps is that local knowledge information is fundamentally spatial and maps are all about the language of space. Since maps are seldom bound to written language, they have proven time and again to bridge the gap between language and culture in terms of communicating ideas and information.

In addition to that, a proper management of flood risk will be effective through strengthening institutions and a strong collaboration between the different stakeholders. That why we are advocating for:

- The reinforcement of coordination between the different actors in flood risk management such as: Watersheds agency, Wilayas, Public Work Direction, Water agencies, local authorities, population…
- The update of laws or legislative documents as far as urban settlement is concerned.
- The construction of new dams for flood control.

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Appendices

Manning Coefficient for some channels

Types of channel and description	Minimum	Normal	Maximum
Main Channels			
a. clean, straight, full stage, no rifts or deep pools	0.025	0.03	0.033
b. same as above, but more stones and weeds	0.03	0.035	0.04
c. clean, winding, some pools and shoals	0.033	0.04	0.045
d. same as above, but some weeds and stones	0.035	0.045	0.05
e. same as above, lower stages, more ineffective slopes and sections	0.04	0.048	0.055
f. same as "d" with more stones	0.045	0.05	0.06
g. sluggish reaches, weedy, deep pools	0.05	0.07	0.08
h. very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.1	0.15
2. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages			
a. bottom: gravels, cobbles, and few boulders	0.03	0.04	0.05
b. bottom: cobbles with large boulders	0.04	0.05	0.07
3. Floodplains			
a. Pasture, no brush			
1.short grass	0.025	0.03	0.035
2. high grass	0.03	0.035	0.0
b. Cultivated areas			
1. no crop	0.02	0.03	0.04
2. mature row crops	0.025	0.035	0.045
3. mature field crops	0.03	0.04	0.05
c. Brush			
1. scattered brush, heavy weeds	0.035	0.05	0.07

2. light brush and trees, in winter	0.035	0.05	0.06
3. light brush and trees, in summer	0.04	0.06	0.08
4. medium to dense brush, in winter	0.045	0.07	0.11
5. medium to dense brush, in summer	0.07	0.1	0.16
d. Trees			
1. dense willows, summer, straight	0.11	0.15	0.2
2. cleared land with tree stumps, no sprouts	0.03	0.04	0.05
3. same as above, but with heavy growth of sprouts	0.05	0.06	0.08
4. heavy stand of timber, a few down trees, little undergrowth, flood stage below branches	0.08	0.1	0.12
5. Same as 4. with flood stage reaching branches	0.1	0.12	0.16
4. Excavated or Dredged Channels			
a. Earth, straight, and uniform			
1. clean, recently completed	0.016	0.018	0.02
2. clean, after weathering	0.018	0.022	0.025
3. Gravel, uniform section, clean	0.022	0.025	0.03
4. with short grass, few weeds	0.022	0.027	0.033

Oued Mehraz cross sections output

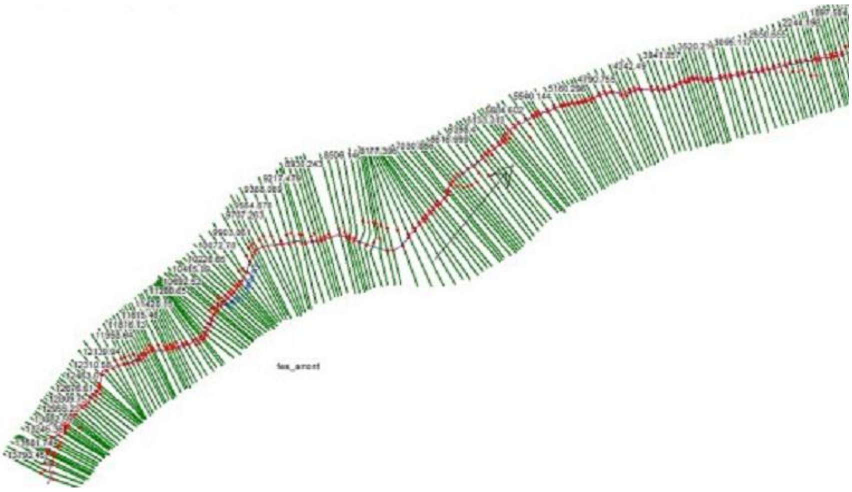
Plan: Plan 01 NouveauMehraz 3 RS: 100 Profile: 10 years

E.G. Elev (m)	457.21	Element	Left OB	Channel	Right OB
Vel Head (m)	12.74	Wt. n-Val.	0.030		0.030
W.S. Elev (m)	444.47	Reach Len. (m)	1.00	1.00	1.00
Crit W.S. (m)	446.79	Flow Area (m2)	5.63		0.68
E.G. Slope (m/m)	0.500674	Area (m2)	5.63		0.68
Q Total (m3/s)	94.45	Flow (m3/s)	90.68		3.77
Top Width (m)	3.39	Top Width (m)	2.93		0.46
Vel Total (m/s)	14.96	Avg. Vel. (m/s)	16.10		5.54
Max Chl Dpth (m)	4.47	Hydr. Depth (m)	1.92		1.49
Conv. Total (m3/s)	133.5	Conv. (m3/s)	128.2		5.3
Length Wtd. (m)	1.00	Wetted Per. (m)	10.68		5.98
Min Ch El (m)	445.80	Shear (N/m2)	2590.47		558.29
Alpha	1.12	Stream Power (N/m s)	1005.44	0.00	0.00
Frctn Loss (m)		Cum Volume (1000 m3)	2.22	3.38	1.38
C & E Loss (m)		Cum SA (1000 m2)	1.49	2.07	0.77

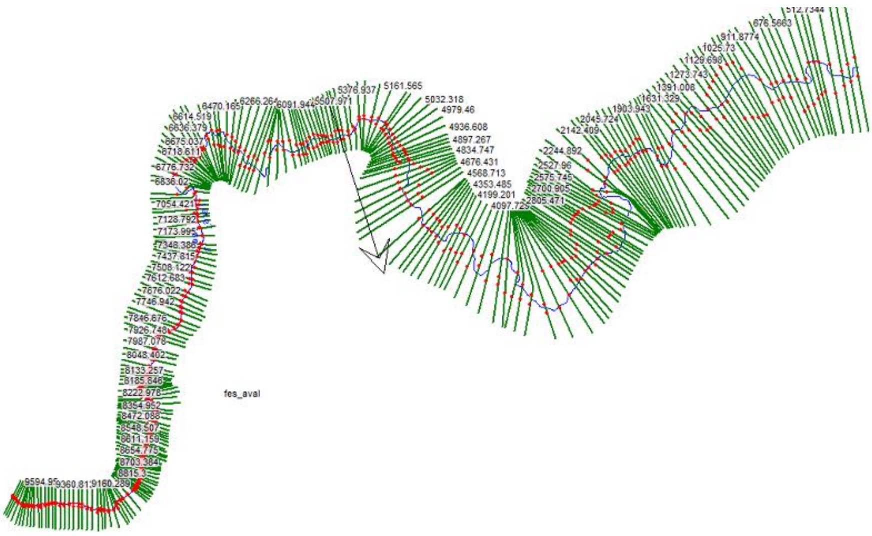
Oued Boufekrane cross sections output

Plan: 12 Boufkrane 2 RS: 100 Profile: 10 ans					
E.G. Elev (m)	484.78	Element	Left OB	Channel	Right OB
Vel Head (m)	24.18	Wt. n-Val.		0.030	
W.S. Elev (m)	460.59	Reach Len. (m)	0.50	0.50	0.50
Crit W.S. (m)	462.34	Flow Area (m2)		2.02	
E.G. Slope (m/m)	1.231612	Area (m2)		2.02	
Q Total (m3/s)	44.00	Flow (m3/s)		44.00	
Top Width (m)	3.79	Top Width (m)		3.79	
Vel Total (m/s)	21.79	Avg. Vel. (m/s)		21.79	
Max Chl Dpth (m)	0.59	Hydr. Depth (m)		0.53	
Conv. Total (m3/s)	39.6	Conv. (m3/s)		39.6	
Length Wtd. (m)	0.50	Wetted Per. (m)		4.47	
Min Ch El (m)	460.00	Shear (N/m2)		5459.31	
Alpha	1.00	Stream Power (N/m s)	1867.24	0.00	0.00
Frctn Loss (m)		Cum Volume (1000 m3)		0.40	
C & E Loss (m)		Cum SA (1000 m2)		0.85	

Cross sections

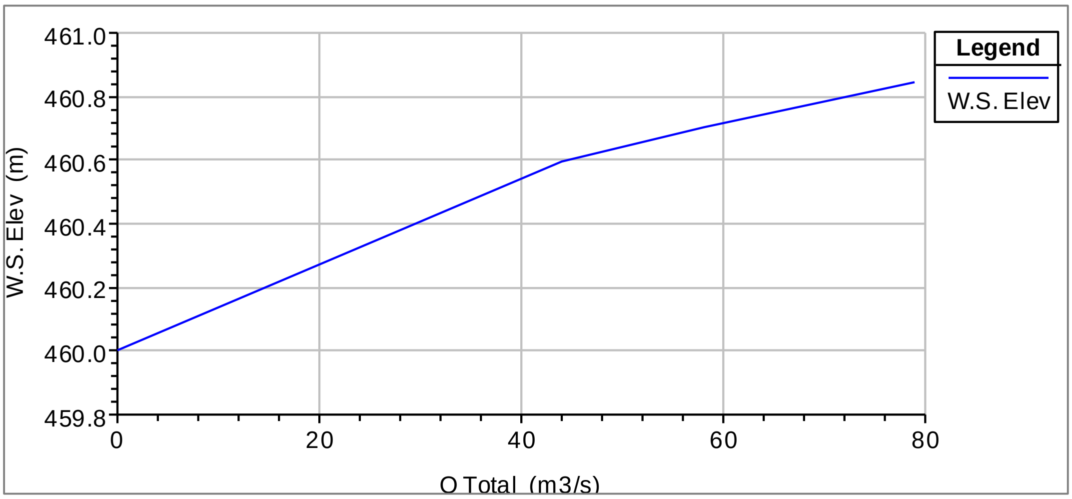


Upstream Oued Fez

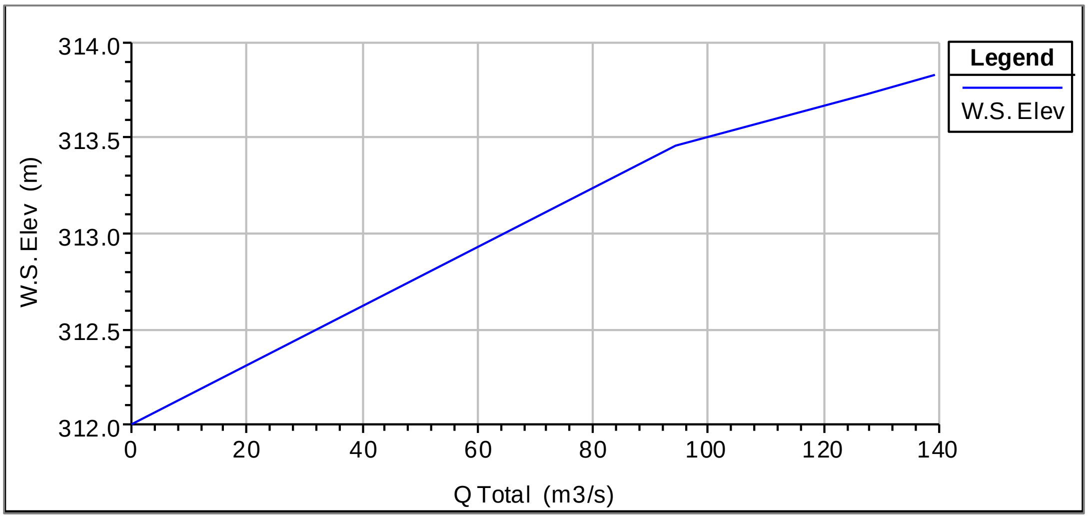


Downstream Oued Fez

Rating Curve



Oued Boufekrane rating curve



Oued Mehraz rating curve