

# **Flood Risk assessment in Barcelonnette, France**

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# **Flood Risk assessment in Barcelonnette, France**

by

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*This thesis is dedicated to all those helpless people in the world who are facing the catastrophe of nature every now and then. May there be a day when no one suffers from such trauma anymore.....*

## Abstract

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Flood risk is the result of natural processes and anthropogenic activities. It calls for a close assessment of all issues related to extreme events with a view to correctly evaluate their impact and the risk associated with them. An integrated hydrological modelling approach for risk assessment and its effect on the study area in Ubaye River valley (France) has been adopted in this research. The steps entailed in the research can be broadly divided into four major parts. Firstly, detailed investigations of the available historical data were made to understand the probabilistic occurrence of the events. These were done by analysing the hydro-meteorological and cartographic data with statistical evaluation of the events. The second step involved modelling of events with selected return periods using SOBEK1D2D hydrodynamic model using a DSM that was generated by combining the natural terrain and man-made topography. The selected return periods used were 75, 100, 200, and 500 years. The model was calibrated based on varying Manning's friction coefficient within the channel to obtain the best results using observed data for water depth for a recent event. In the third step, a vulnerability assessment was carried out by comparing depth and the duration of the selected flood events with the physical elements at risks. Finally, integrated risk assessment maps were prepared by combining the elements at risk with, the data on flood characteristics and stage damage functions. Risk maps were generated based on types and functions of the elements at risks for a better understanding of the flood situation in the area. The results from this research provided useful information on risk prone areas and the elements at risk especially near the vicinity of the river. The methodological approach of reconstruction of the events using SOBEK had achieved a result up to an accuracy level ranging between 0.29 m to 0.9 m after calibration of the model. The vulnerability assessment of the physical elements at risk had been achieved using stage damage functions used in Germany, United Kingdom and France. Risk assessment was analysed in terms of economic damage caused by differential effects of flood hazard. The incorporation of land use, economic data and flood characteristics information resulted in the level of risk delineation in different zones. The result from this study were further investigated in a comparative analysis of the changes that had occurred due to changes in protection plans like Prévention des Risques naturels prévisibles (PPR) and Plan d'Exposition aux Risques (PER) for the past 25 years. The final outputs from the study have a potential for flood risk communication among people and an impact on the strategic management decisions taken by the authorities and policy makers.

*Key words: DSM, SOBEK-1D2D, Hydrodynamic model, Friction, Hazard, Vulnerability, Risk.*

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*Namrata Bhattacharya*  
*March, 2010*  
*Enschede*  
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## List of Abréviations

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ANUDEM	Australian National University Digital Elevation Model
DTM-	Digital terrain model
DSM-	Digital surface model
DDA-	District development authority
PACA -	Provence-Alpes-Côte d'Azur
PPR-	Prévention des Risques naturels prévisibles
PER-	Plan d'Exposition aux Risques
POS-	Plan d'Occupation des Sols
PCS-	Plan Communal de Sauvegarde
RTM-	Restauration des Terrains de Montage
Q-Q plot	Quantile-Quantile plot
1D-	One Dimensional
2D-	Two Dimensional

## **1. Introduction**

### **1.1. Research Background**

Floods are the most common and disastrous natural threats that the world is facing today. They cause more damage and destruction than any other hydro-meteorological phenomenon (NOAA/NWS, 2009). Floods have taken lives of thousands and caused destruction of properties costing billions of Euros. They account for about 20% of the total death toll and 33% of the destruction in terms of economic loss globally as compared to other natural disasters (IF-NET, 2005). With the rapid level of urbanization and infrastructural development, floods in urban areas in Europe have become more frequent and expensive. For example, the major floods in rivers of France, Germany, Italy, Spain and UK in the last century cost millions of dollars (Conway, 2000).

It is historically proven that flood plains are the most attractive areas for settlement and development (Alkema, 2007). However, The human activities may sometimes cause interference with nature resulting in destructive floods (WMO/GWP, 2005). To prevent such situations it is important to have a clear knowledge of how the development and management activities in an area have an impact on the flood risk. There may be a trade-offs between the developmental activities and the level of risk and decision making. There has been a lack of holistic approach in the assessment of hazard and the corresponding risk. Therefore, it is necessary to assess the hazard in such a way that would be a true reflection of the real world scenario. This would help to gain an improved knowledge about the risk involved. Consequently it is vital to reduce the problem by developing an understanding of the characteristics of the nature (flood behaviour) and causes that may lead to such events. This is possible through simulation of the different scenarios using various sophisticated flood models available.

However, generation of the real world situation or prediction for the future is difficult and needs expertise. It needs thorough investigation and detailed analysis of the available data in terms of quality and accuracy. Moreover, transformation of the hazard into risk requires generation of appropriate relationship between the hazard magnitude and the degree of damage of the different elements at risk (Smith, 2001).

The results from such studies are expected to help the society to be aware of the risk of flood and to take preventive actions for the future. There has been a high stimulus given to the studies of urban flood management in the recent years (Ashley, 2007). Therefore, a renewed database of vulnerable elements at risk in the study area in addition to hazard and risk analysis will be helpful to the local authority for future development and management plans.

## **1.2. Research Problem**

Barcelonnette is a town situated in the flood plain of the Ubaye River valley. It is a typical tourist town with expanding utilization of land in the flood plain area. The main reasons for the urban expansion are economic growth and the development of the town through tourism. Previously, this area was already suffering from many hazards including landslides, debris flow and inundation. These were as a result of the geology, geomorphology, climatic characteristics and evolving land use of the area. These factors are favourable to various levels of slope instability and landslide susceptibility. There were several evidences of torrential events which were characterized by significant number of debris flows (Maquaire et al., 2003, Flageollet et al., 1999). These events were controlled by construction of a number of check dams for protection of the town as well as channelizing the river within the boundary of the town. (OMIV, 2007).

There was large influence of the anthropogenic activities within the catchment and the system decayed with changing land use (Flez, 2003). With the rapid development of the Barcelonnette town as a major business centre, farming and other human induced activities increased, resulting in large scale deforestation for land clearing (Blijenberg, 1998). This led to increase in erosion load from the slopes, resulting in blocking of the check dams through sediment concentration. A renewed phase of flooding occurred when the area faced the regional event of flooding in 1957 (Liébault and Piégay, 2002). There were other small events that occurred after this event but because of the protection measures taken after the 1957 event they were not given too much importance.

The recent damages that occurred due to the peak discharge of the river Ubaye in May 2008 have grabbed the attention of researchers and authorities to assess the flood hazard of the area. Since there was no prior research in the field of flood hazard, this study will be a useful input for the local authorities for management and planning of the town.

This study will focus on the inundation problem of the town. The hazard and the associated risks will be investigated and the scenarios will be generated looking into the past to predict for the future. Further analysis will concern in the transformation of flood hazard into risk through identification of the vulnerable elements.

## **1.3. General Objective**

The main focus of the study was to gain a better understanding of the flood hazard by hydrological model simulation and assessing the risk situation of the Ubaye River on the Barcelonnette town. It also aimed at investigating the possible consequences of hazard scenarios in the assessment of risk.

## **1.4. Research Objectives and Questions**

Based on the research objective the following questions are formulated

- 1. To Generate the Digital Surface Model (DSM)**



- What are the significant elements that should be taken into account in the construction of the DSM?
  - What level of accuracy of the DSM is appropriate for urban flood modeling?
2. To assess the flood hazard using SOBEK 1D2D
    - What are the appropriate hydrographs (in terms of peak discharge and shape) to simulate floods with different return periods?
    - How to assess the flood characteristics for different return periods?
    - What are the spatial extents of the flood for different return periods?
    - How to reconstruct the flood event of 1957 and 2008 using the available data?
    - How does the output of the model correspond to the flood scenarios?
    - What is the sensitivity on the model with reference to friction values?
  3. To identify the physical elements at risk and their vulnerability
    - What are the different physical elements at risk?
    - What is the level of vulnerability as a function of the flood characteristics?
    - What will be the effect on the present elements at risks based of 1957 flood event?
  4. To assess the flood risk
    - What is the degree of risk as a function of flood characteristics?
  5. To investigate the effect of flood plain developments on the level of flood risk over time
    - How the changes in prevention plans affected on the level of risk?
    - What will be the risk consequences on present economy on the flood plain?

### **1.5. Thesis Outline**

The entire thesis has been divided into seven chapters.

The first chapter introduced the research background, problem statement followed by the research objectives and questions.

The second chapter provided detailed literature review including explanations on the various processes that have been used for the research. It discusses the issues involved in hydrological modeling both for 1Dimensional and 2 Dimensional models and the 1D2D SOBEK model. The generation of DEM and issues related to input data were discussed and the views of experts in dealing with specific problems related to hazard assessment were cited. A detailed description of the different vulnerability and risk assessment criterions were discussed based on the literature and finally the uncertainties in such studies related to all the different phases of investigation were discussed.

The third chapter described the historical background and the location of the study area. It also provides a brief overview of the climatic, geological, soil, land-use patterns and socio-economic condition of the area.

The fourth chapter dealt with the description of the data and its acquisition used in the study, involving the details of the existing data and the data collection conducted during fieldwork. It also involves the description of the methodology used in the research with reference to each objective.

The fifth chapter described the results obtained at different stages of hazard assessment in the research. This chapter was divided into several subtopics based on the generation of DSM and analysis of data, hazard assessment using SOBEK1D2D flood model. It also included the parameters affecting the flood modeling for example surface roughness, boundary conditions and sensitivity analysis of the model.

The sixth chapter dealt with the risk assessment processes with response to the vulnerability of the elements at risk and the hazard assessment. Further assessment of the level of annual risk for the different elements and land use types in terms of economic damage had been performed. Furthermore comparative analysis between the prevention plans and risk maps were performed with the results obtained from the present study.

The final chapter concluded the entire research and provided further recommendations for the individual sections of the research.

## **2. Literature Review**

This chapter reviews the summary and synthesis of various literature related to the field of research. It incorporates the views and ideas which are important to build a strong background for gaining the research objectives. A detailed review of the past studies and the thoughts developed by experts of the field of study are the base of many of the methodologies and processes in the forthcoming chapters.

### **2.1. Inventory Research:**

A special attention was given to the documentary evidences existing for the past inundation events in the area. This included both the advantages and disadvantages. Further, significant results were also based on the available historical database. This gives the knowledge about the historical perspective in terms of data and their impact on the area.

#### **2.1.1. Historical Geomorphologic Events From Archives**

Examination of various archive documents has helped in gathering knowledge about the inventory of various hazards which has occurred for since 1850's. There has been 958 references (Flageollet *et al.*, 1999) of catastrophic events since then in five different categories like climatic irregularities in the form of storm, hail, drought and gail; torrential flows like overflows and inundation, debris flows and gullyng; landslides in the form of rock fall, rock slip and mud flows; snow avalanches and earthquakes. Among them 60% of the occurrences were in the form of torrential flows (Weber, 1994). This is indicative of the torrential nature of rainfall and the draining of large number of torrents in the valley complimented by snow melts. It has been confirmed by literature that historical flood studies has major interests in extreme flood event analysis. They provide higher scope for hydraulic and statistical analysis and also the reaction of the society towards the catastrophic event (Coeur and Lang). These experiences build up in capacity generation and mitigation of the prevention policies.

#### **2.1.2. Past Studies**

Based on archive literature (Flageollet, 1996) there were six cases of major inundations and 15 other cases of floods inclusive of other phenomenon like debris flow and over flows are significant since 1850 though the number of references were much higher than that (around 428). But apparently these included all those events also which were not significant enough to be called hazards. Out of the 428 references 13% included debris flow, 12% with inundations and 2% with gullyng while rest of the 73% was just torrential flows. Among all these references only 15 events can actually be accredited as floods (Flageollet, 1996). A detailed picture of the events occurring from 1850 to 1990's has been shown in the following graph (fig.2.1). Since 1990's up to 2008 there were mainly 8 major and minor torrential events that took place in the area (Met. Dept. Barcelonnette).

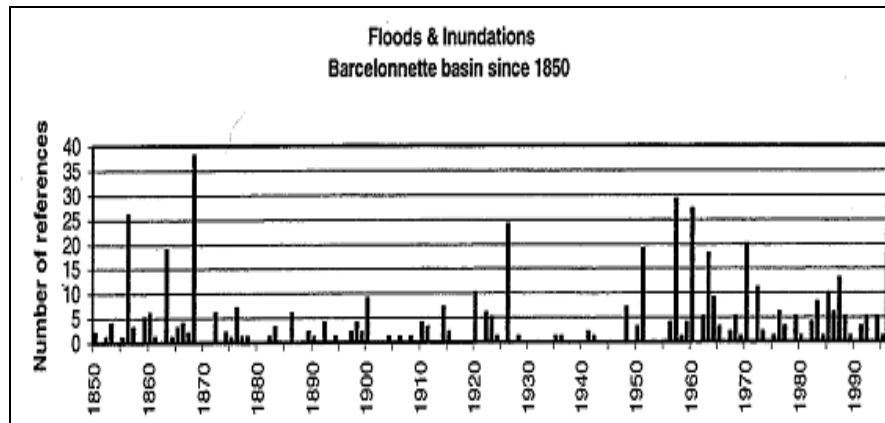


Figure.2. 1. Annual occurrence of Flood event Inventory since 1850 adapted from (Flageollet, 1996)

Based on the occurrence of events it can be demonstrated that there were three distinct period of fluctuations in the events(Weber, 1994). These characteristic periods can be distinguished as period until 1914, 1915-50 and 1950 till date. The first period had experiences great many numbers of events in the area mainly due to the fact that there was large scale deforestation and no proper laws for corrective actions. The major events during this period occurred in 1856, 1863, 1868 and 1874. Since 1864 some corrective activities and reforestation actions took place and as a result the benefits could be seen during the next phase where there was a significant fall in the major events with one exception in 1926(Weber, 1994).

But the collapse of the systematic corrective works had an effect on the number f events and it started increasing due to lack of maintenance during the next phase(Flageollet, 1996). The regional events during the third phase are centenary flood in June 1957 including other events in 1951,1960,1963,1970, 1983, 2003, 2008etc.

There are two major studies done on the historical event of 1957 by (Tricart, 1958) and (Lecarpentier, 1963) which from where the knowledge of the characteristics of the event were obtained. There are some official reports obtained from the Museum of Jausier municipality where the immediate measures and policies after the event were documented. The estimated discharge and hydraulic conditions of the basin for the event was obtained from the thesis of Le Carpentier and the general climatic condition of the event and related meteorological effects on the area during that time can be understood from the report of Tricart. For the 2008 event mainly newspaper reports and personal interviews with the officials from the municipality and RTM were the sources of information.

### 2.1.3. Limitations Of Inventory Research

Establishing any kind of conclusions based on the archives and the number of events was not very easy due to the fact they have been often over or underestimated. There was a major problem of accuracy in this regard. For instance the regional events like the inundation of 1856 and that of 1957 have been recorded in each and every

commune that was affected by it and the consistency in the reports varied in different communes (Weber, 1994). It was also a problem for datasets collected from different sources having some discrepancies between them and sometimes they are biased (Blijenberg, 1998).

## **2.2. Flood Frequency Analysis**

For the predetermination of flood frequency in an area the most appropriate was the probabilistic approach of characteristic quantification of the flow variation within the hydrologic regime (Robson, 1999). It can explain in terms of probability of occurrence of the regular events and events which are rare but may occur after a particular time interval. It has proved to be a remarkable tool for decision support system (Javelle, 2001). The Gumbel frequency curve (El-Naqa and Zeid, 1993) for extreme value distribution was tested to be an important application to test the relationship between magnitude of extreme event and their probabilistic distribution. The frequency estimation in areas with limited flood records can be estimated using mean annual flood representing annual maximum flow in the basin (Nouh, 1987). The distribution of best fitted probability functions can be investigated using statistical models for utilization in peak flow analysis. Two more approaches of flood frequency analysis for extreme events have been discussed for extreme events (Robson, 1999). The first approach was based on estimation of peak flow and the event flow and the second technique was continuous simulation techniques using parameter sparse modeling in data poor regions (Calver *et al.*, 2009). Pearson's statistics was an important tool for analysis of goodness of fit of the data and multiple response observation for the same combination of explanatory variables (Smyth, 2003). After the analyses of the frequency of the events are done the next step was the selection of an appropriate model for simulation of the events.

## **2.3. Hydrodynamic Models For Flood Hazard Modeling :**

Modeling flood hazard in an urban setting given the magnitude of potential loss and damage caused by such event has made it increasingly relevant. For proper estimation of flood hazard the selection of an appropriate model was necessary among numerous available models. The existing 1D model and 2D model had their own advantages and disadvantages which encouraged the integration of the methods (Rahman, 2006). The SOBEK model used in the study was developed by WL Delft Hydraulics. This is a dynamic model with the modules for both 1D domain within the channel and 2D domain on the overland module (Delft, 2009).

### **2.3.1. 1Dimensional (1D) Hydrodynamic Modeling**

The 1D model are simplified models which characterizes the terrain through a series of cross sections and calculates the water depth and the flow velocity perpendicular to the direction of the flow (Rahman, 2006). The direction of the river flow path was pre-defined for such models. Interpolations of the sections in between the cross sections were calculated by the model. These models are well suited for well defined valleys where direction of flow is well defined (Alkema, 2007) and simulates better results when the water stays within the channel. However, for a complicated terrain

and especially for urban flood modeling where there is perpendicular flow of water in the direction of the main flow or for overbank flows the model neglects those values leading to an erroneous result (Werner, 2004). Moreover, in urban areas the complexity of the infrastructures such as roads and buildings gets limited by the assumptions in calculation of flow for 1D model (Mark *et al.*, 2004).

### **2.3.2. 2Dimensional (2D) Hydrodynamic Modeling**

The relatively new tool in flood modeling is the 2D hydrodynamic model. It has the advantage over 1D models in the way it calculates the flow of water non-parallel to the main river flow and overland flow. It calculates the flow in both spatial dimensions (Alkema, 2007). All inputs and outputs in 2D model are assumed to be uniform within a single pixel (Rahman, 2006). These models are also capable of providing information about spatial distribution, variation of flow velocities and extend over user defined time frame (Tennakoon, 2004). Therefore these models are useful for simulation of more comprehensive flood hazard and risk assessment in areas of complex topography. In spite of its various advantages (Werner, 2004) argued that the requirement of high quality data and long computation time for proper simulation of flood sometimes limits the feasibility of such complex models.

### **2.3.3. 1D2D SOBEK Model For Flood Modeling**

Studies revealed that the flow of water over terrains was better modeled by 2D models and the flow within confined channels was better represented by 1D flow models (Leandro, 2009). This tradeoff between the 1D and 2D models calls for an integrated 1D-2D modeling approach. SOBEK-1D2D model developed by WL\_Delft Hydraulics in The Netherlands (Delft, 2009) is one of the sophisticated models in modeling flood in complex terrains. It has the capacity to model both in one dimension and two dimensions. It has the unique capability of conservation of momentum and mass. It integrates the 1D channel flow with 2D overland flow (Alkema, 2007). The assessment of suitability of a model was based on its performance to different magnitudes of flood (Tennakoon, 2004). The usability of the model can be evaluated by consistency in calibration which justifies its suitability for practical uses (Horritt and Bates, 2002). Studies (Alkema *et al.*, 2004) indicate that the SOBEK1D2D model was designated to simulate flow of water in both within the channel and overland flow through complex topography for different magnitudes of flood (Rahman, 2006). While another study (Lomunder, 2004) evaluated the model after calibration for two different scenarios and showed satisfactory consistency in their results.

### **2.3.4. Model calibration and sensitivity analysis**

Model parameterization needs to be incorporated to get a better result with multidimensional real world flow pattern (Arcement *et al.*). The study by (Nash and Sutcliffe, 1970) determined the parametric values of models based on set pre-conditions through automatic optimization. This determined the index of agreement or disagreement between observed and computed values. Calibration process used

by (Lomunder, 2004), for determination of applicability of three different models in different flood scenarios indicated that in spite of higher  $R^2$  values for the 1D2D model the results for the 2D model were more plausible. Data non availability and processing problems were considered to be the reason for such results. Other studies like (Rahman, 2006) and (Peters, 2003) showed that 1D2D models are well suited for decision making processes for management of flood plain investments. The variable that determine the flow of the water within the channel are the friction coefficients like bed friction and wall friction. These two variables were considered for calibrating the model to evaluate its performance.

The model sensitivity was highly influenced by the flood plain topography and hydraulic friction in propagation of inundation (Hesselink et al., 2003). The bed friction can be defined as the friction between the flowing water and the channel bed. It exerts a resistance to the flowing water always in the direction opposite the water flow (Dhondia, 2002). The size of the pebbles within the channel and the nature of the bed act as an important factor in the determination of the friction value (Arcement et al.). The flow condition of water within the water courses are usually determined by this force caused with earth's gravity (Hydraulics, 2002). The wall friction on the other hand acts as an added resistance as a result of vertical obstacles such as under water vegetation within the channel and trees and houses in the 2D domain (Delft, 2009). Werner et al., (2005) expressed that the channel friction values play a major role in flood model calibration process than overland friction values. Therefore focus should be provided more on the main channel roughness.

The historical data allows the evaluation of the model for events of long return periods. Concerns have been expressed regarding simulation results and uncertainty in Manning's "n" roughness coefficient for reconstruction of historical flood events. The results were affected up to 20% in case of changing the "n" values by 25% (Wohl, 1998). The changes in roughness coefficients are also affected by channel parameters such as vegetation density and height, amount of debris and sediments and meandering of the channel thus affecting the simulation results (Arcement et al.). Furthermore the sensitivity of a model increases with the number of input factors considered (Hall *et al.*, 2005) increasing the level of uncertainty. the detailed analysis of the calibration and sensitivity of the model can be seen in section 5.3.3.

#### **2.4. Digital Terrain Model (DTM) and Digital Surface Model (DSM)**

An important input of hydrodynamic modeling is the proper representation of terrain on which the model will work on. "Commonly, flood model applications are reported successful in topographically simple areas where topography only changes gradually and where topography was simulated by DEM's of relatively low resolution" (Haile and Rientjes). It was easier to model in areas which are not complex in character while simulation was difficult where it involves other features like roads, buildings, river banks and dykes which influence the flow dynamics and flood propagation. These features are complicated to be accounted for in model setups (Domingue, 1988). There was a need for hydrologically corrected surface for proper simulation of the real world scenario. This entails for appropriate selection of the interpolation method for flood hazard studies.

### 2.4.1. Interpolation

The method of interpolation for generation of the DEM was a critical issue in flood hazard studies. Nevertheless, it was decided based on several literature such as (Maune, 2007) ,(Kienzle, 2004) and (Tarekegn, 2009) the interpolation method of Australian National University Digital Elevation Model (ANUDEM ) was selected to be one of the appropriate methods for DEM interpolation for flood modeling. It uses advanced krigging as the interpolation method. According to (ESRI, 2009) the principle behind the interpolation method was studied and the justification for its use in the study was assessed. ANUDEM was developed by Hutchinson (Hutchinson, 1996). This interpolation method was considered to be designed to create hydrologically correct surfaces (Rahman and Alkema, 2006). This method automatically removes spurious sinks (Sinha, 2000) and advantageous for faster computation, lowering “roughness penalty” (Rahman, 2006) and has a drainage enforcement algorithm for preserving the natural sinks in the area. This method when compared to other methods like IDW and normal krigging (Kenny and Matthews, 2005) was as good as their level of accuracy (Rahman, 2006).

### 2.4.2. Resolution and Accuracy Assessment Of DEM

Selection of optimum pixel resolution for hydrodynamic modeling was essential for flood modeling. According to (Tennakoon, 2004) and (Rahman, 2006) the optimum pixel size for various applications of flood modeling are summarized in the following table.

**Table 2. 1.** Showing optimum resolution for DEM based of different applications

<b>Applications</b>	<b>5 m DTM</b>	<b>7.5 m DTM</b>	<b>10 m DTM</b>
Urban area study			Adequate
EIA related study for individual structures	Adequate		
Small scale EIA study for reclamation			More than 10
Detailed study based on velocity, sedimentation and erosion		Adequate	

It was also identified in the study by (Maune, 2007), that higher vertical accuracy and higher resolution of data are required for flat lower part of the riverine flood modeling rather than in the mountainous area (Ruyver, 2004). The significance of DEM resolution and effect of interpolation methods on the different terrain derivatives were proposed to be non-realistic when resolution coarser than 20 m were used for modeling the event (Kienzle, 2004). In case of non-existence of non-



existence of ground truth data the accuracy assessment of DEM can be done using the hill shade generation through visual interpretation (Maune, 2007).

## 2.5. Flood Hazard Estimation

According to (UN-SIDR, 2004), hazard can be defined as the “potentially damaging physical event, phenomenon or human activity that may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation. This event has a probability of occurrence within a specified period and within a given area and has a given intensity”. The studies related to analysis of physical aspects and phenomenon through collection of historical records is called hazard assessment. Flood Hazard estimation is based on the factors such as the triggering factors causing the hazard, their spatial extent, duration and time of onset, including their frequency and magnitude of occurrence and secondary events influencing the event if any (Geohazards, 2009).

The hazard estimation is also based on the output of the model simulation in the form of parameter maps such are flood velocity, flood depth and flood impulse(Alkema, 2007). The pre-requisite for flood hazard is estimated by its frequency or return periods(Apel *et al.*, 2006). The estimation of return periods are calculated by using statistical models for flood frequency probability analysis (Anderson and McDonnell, 2005). Hydrographs for different return periods are the basis for understanding the hydrologic response of the basin (Jain, 2006).Hence the computation of this parameter is essential for any flood study. It is one of the major inputs of the model as well. The shape and values of the hydrographs plays an essential role for appropriate model outputs (Weingartner, 1990). It is also argued that the magnitude and duration of the flood in different time scales changes.

According to (Smith, 2001), the impact of flood hazard can be characterized by multiple aspects such as effect to human beings to physical infrastructures and to environment. The relationship between flood characteristics and the adverse effects caused by it can be constructed meaningfully for creation of hazard maps (Rahman, 2006). The hazard categories identified by (CSIRO, 2000) based on depth and velocities of flood water can be shown in the table 2.2 based on a 100 year event.

**Table 2. 2 .Flood hazard categories based on CSIRO (2000)**

<b>Hazard category</b>	<b>Base Flood event</b>	<b>Characteristics</b>
Low	100yr	Areas that are inundated in a 100yr flood, but the floodwaters are relatively shallow (typically less than 1m deep) and are not flowing with velocity, adult can wade.
High - Wading Unsafe	100yr	The depth and/or velocity are sufficiently high that wading is not possible, risk of drowning.

High - Depth	100yr	Areas where the floodwaters are deep (> 1m), but are not flowing with high velocity. Damage only to building contents, large trucks able to evacuate.
High Floodway	- 100yr	Typically areas where there is deep water flowing with high velocity. Truck evacuation not possible, structural damage to light framed houses, high risk to life.
Extreme	100yr	Typically areas where the velocity is > 2m/s. All buildings likely to be destroyed, high probability of death.

Hazard assessment is interrelated to vulnerability of the elements at risk and further assessment of degree of risk. Combinations of the flood characteristics parameters are required to assess the actual hazard in an area as indicated by Tennakoon (2004) in his study in Philippines.

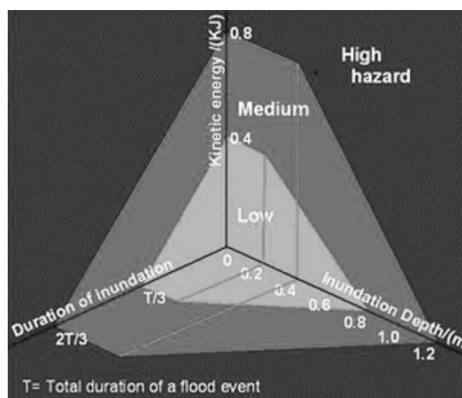


Figure.2. 2.Flood Hazard classification based on multiple flood characteristics, (Tennakoon, 2004)

## 2.6. Elements At Risk And Vulnerability assessment

According to (Nott, 2006) the elements at risk can be defined as the level of exposure with reference to buildings/ infrastructures, population, economic activities, public services and utilities which can be impacted by hazard. The quantification of vulnerability depends on the degree of loss to a given element at risk at a given severity level (UNDP,1994 cited in (Wigati, 2008)). This in turn is determined by conditions or processes that increases the susceptibility of the community (physical, social, economic or environmental) (UN, 2006). The focus of this study is mainly on physical vulnerability. The study in Naga city Phillipines by (Hasiholan, 2006), conducted the vulnerability assessment by gathering information through interviews. However such methodologies are difficult to conduct in case of

historical events where local people might not be able to give proper information about the old events (Lecarpentier, 1963). Therefore, an alternative method to this was used by several studies emphasizing the use of stage- damage functions based on depth, duration or intensity of flood event. Several countries in Europe do not have widespread national damage functions and vulnerability assessment is done at local levels. Countries such as Germany, United Kingdom and the Netherlands use the damage functions more often than others like France. Therefore in this study focus on the assessment of damage has been done using functions from Germany and UK (FLOW, 2006). A study in Quebec, Canada has been used by France was also considered to highlight the effect of these curves in damage assessment. White (1964) cited in Sangala (2006) indicated the damage curves used for assessment of buildings and other physical elements based on their type and material of buildings. There are several advantages and disadvantages of using stage damage functions as indicated by (Alkema, 2007) it is the most widespread technique used for vulnerability assessment for flood risk management.

## 2.7. Risk Assessment

The risk assessment is an integrated part of the flood management processes of achieving reliable safety measures against catastrophic events (ICT, 2006). Risk assessment can be defined as the process of making a decision or recommendation on whether existing risks are tolerable and present risk control measures are adequate and if not whether the alternative risk control measures are justified or will be implemented (Geohazards, 2009). For calculating risk quantitatively where vulnerability of the physical elements at risk in relation to intensity of hazard can be derived from the basic equation:

$$\text{Risk} = P_T * P_L * V * A \dots \dots \dots (\text{Geohazards, 2009})$$

Where,

$P_T$  is the temporal probability of occurrence of a specific hazard scenario with a given return period in an area

$P_L$  is the locational or spatial probability of occurrence of a specific hazard scenario with a given return period impacting on element at risks

$V$  is the physical vulnerability, specified as the degree of damage to a specific element at risk given the local intensity caused due to occurrence of hazard scenario

$A$  is the quantification of specific type of element at risk evaluated.

Risk assessment can be qualitative, semi-quantitative or quantitative. However the success of risk assessment depends upon the correct evaluation of the value of the elements at risk (Badilla, 2002). This further depends upon the information available related to the characteristics of the risks and cause of the damage (Dutta, 2001), (Jonkman et al., 2008). This can be type, age, number of floors, material and condition of the elements within the study area (Merz et al., 2004). This study has also emphasized that the hazard potential is subject to temporal changes which further affects the framework of risk assessment. Therefore risk assessment in terms of potential monetary damage assessment (Kazama et al., 2009) helps in enhancing

the coping capacity of the people and encourages mitigation measures. The annual average risk may be obtained by generating risk curves based on the total monetary loss for different return periods. The total area under the curve represents the total annual risk for the area of getting flooded (Geohazards, 2009).

However it is not always possible to get the value of the elements at risks precisely and get specific amount of potential risk in monetary terms. Therefore the concept of qualitative risk based on experience and expert knowledge is also very essential (Merz and ... 2004). The Australian Geomatics Society (AGS, 2000) defines qualitative risk as a way to express the quantitative values for risk. They recommend that it is better to express the risk factor in qualitative terms or in semi qualitative way. (Hearn and Griffiths, 2001) emphasized on the importance of qualitative risk assessment in data poor regions qualitative defined the terminology of qualitative risk. Spatial multi criteria evaluation for qualitative assessment of risk was recommended by (Geohazards, 2009) . It plays an important role in decision support system.

EU water directives have declared that a catchment management plan should be developed for each river basin and they should follow international guidelines for standard risk assessment (Erdlenbruch et al., 2009). Different countries in Europe have separate sets of regulations for evaluating calculation for losses. The asset values are calculated either based on the purchase price or the actual price separately for each type of asset (FLOW, 2006).

### 3. Study Area: The Barcelonnette Valley

This chapter describes the location of the study area and the environmental and socio-economic aspects of the area. This will provide a better understanding of the regional characteristics and give an overall impression of the area.

#### 3.1. Location And Historical background

Barcelonnette is a small town situated in the southern French Alps in the department of Alpes-de-Haute-Provence (PACA). Because of its ideal location the town is known as the alpine capital of the Alpes de Haute Provence. The geographical coordinates were 44°23'12"N 6°39'11"E / 44.39°N 6.653°E. It is the sub prefecture of the Alpes-de-Haute Provence department. It is located in the heart of Alpine valley of the river Ubaye. The town was surrounded by high crested mountain peaks about 2800 to 3100 meters a.s.l. The river Ubaye flows through the bowl shaped basin at an average elevation of 1130mts a.s.l.

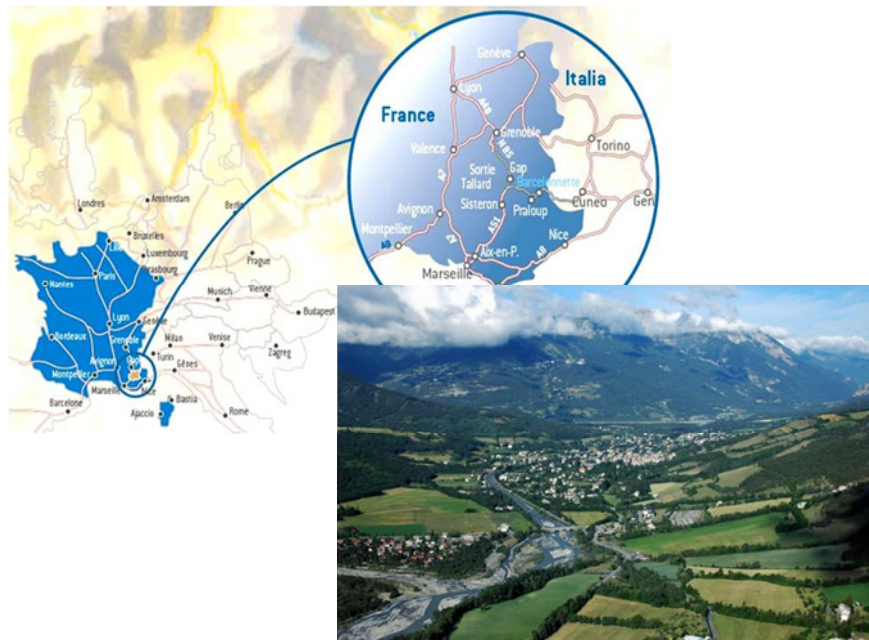


Figure.3. 1. Location of Barcelonnette Town

The town was founded by the count of Barcelona in the year 1231 A.D (information leaflet Barcelonnette Museum). The town had seen large emigration of population to Mexico in the late 19th and the early 20th Century for trade, mainly textiles (Collins,

1995). They came back prosperous and the influence of Mexican culture which can still be seen by the large Mexican villas situated all over the town (Collins, 1995). The study focuses on the town of Barcelonnette along the River Ubaye with a population of 2993 and an area of 16.4 k.m<sup>2</sup> (182.3 persons per square km), (INSEE, 2009).

### **3.2. Climate**

Due to the special position of the region the Barcelonnette basin enjoys a mountainous climate affected by the Mediterranean marine influence moderated by the mountain climate and a mild continental influence. The dry intra-Alpine (Thiery *et al.*, 2007) area has a temperature range between -6 to 20 degrees in extreme cases while an yearly average of 7.5 Degree Celsius. The temperature is also dependent upon altitude and direction of the slopes.

The orographic influence causes precipitation to increase with elevation typical in the form of “attenuated Mediterranean regime”(Weber, 1994). The maximum rainfall occurs generally during the autumn and a secondary peak can be observed during June. Average annual precipitation amounts to 716mm (Based on Meteorological data from Pont- Long, Barcelonnette). Summer rainfalls are largely torrential in nature while winter rainfall is mainly in the form of snow.

Local climate is strongly influenced by general relief and the gradient and the slope orientation which affects the rainfall amount, wind and radiation of sun. These results in the temperature difference between the sun exposed slopes and the sun-shaded slopes. The effect of the Mediterranean climate can be seen by the impact of the warm and dry wind called Sirocco from the south which blows over the entire region resulting high snowmelt in spring leading to high discharge in the River Ubaye. This has also been one of the causes of the last two major inundation events in this area that occurred in spring.

### **3.3. Topography**

The region is surrounded by high mountains with rolling flat topography in the central part, where the town of Barcelonnette is located. It is situated in the flood plain of the river Ubaye. The elevation of the urban area ranges from 1130 m.a.s.l to 1150 m.a.s.l. Barcelonnette is characterized by steep slopes with escarpments of geological-structural origin. Along with the presence of escarpments and flanks there are also existing hummocky terrains in the form of bulges. Clear deformation on the position (lineament) of the trees can be seen on steep slopes in different directions confirming the fact that they have been subject to the earth movement activities (Flageollet, 1996) though they are also influenced by snow, wind, rain and temperature.

### **3.4. Geology And Geomorphology**

The Barcelonnette area has a long and dynamic history of earth movements in the form of landslides, mudslides and debris flows. It is covered in large parts by the “Terres Noires” a predominantly marly dark formation (Antoine *et al.*, 1995). The geology of the area is influenced by high variability of lithologic structures. The

instability of various zones in this region can be largely explained by the presence of erodible structures like black marl and flysch which affects the slopes with severe gully erosion. The continuous change in the land use in terms of clearing for agricultural practices in the last two centuries and instability in the climatic factors has also caused damages in the area (Flageollet, 1996).

The valley bottom of has an extensive coverage of Quaternary deposits with recent alluvial deposit carpet on top of them. “They are formed on the surface of dark Limon deposited during major floods (recent one is in 1957)”(Weber, 1994). The detailed geomorphology map of the Barcelonnette basin is attached to appendix 1.

### 3.5. Lithology And Land Use

The main types of soils in the area are the result of intense erosion from the slopes. Weathering produces massive blocks of sandstone and limestone which disintegrates to form sandy and loamy regolith. Flysch produces smaller or massive plates which break down as sandy and loamy regolith while marls produce silts or clayey regolith in the area(Blijenberg, 1998). There is presence of some isolated arms of old meanders with clay deposits and moraines in the higher slopes (Weber, 1994). Several studies had been done in the area as well as the nearby huge mud-slide area (the Super-Sauze mudslide) to understand the soil surface characterization and observe the influence of infiltration through the surface (Malet et al., 2003).

The present land use of the area is summarized in the table below which indicates the percentage of twelve different types of landuse.The detailed land use map of the area is appended to appendix 2.It is an updated version of the available Land use map for 2008 as part of secondary data.

**Table.3. 1.** Showing % of Land use in Barcelonnette

Land use Types	Area in km <sup>2</sup>	Percentage in total Land use
Coniferous Forest (High Density)	6.61	39.70
Coniferous Forest (Low Density)	1.38	8.31
Broad leaved forest	0.88	5.32
Natural grassland	0.66	3.97
Arable Land	2.80	16.86
Pasture	0.86	5.18
Bare rock	0.91	5.48
Black marl	0.63	3.79
Urban fabric	1.59	9.59
Water course	0.92	0.55
Marshes and water bodies	0.02	0.02
Alluvial deposits	0.20	1.24
<b>Total area</b>	<b>17.51</b>	<b>100</b>

### **3.6. Socio-Economic Condition And Human Interaction**

To understand the present socio-economic condition of the area it is important to look back in history. For a long period of time the area was politically independent (Weber, 1994), and the mainstay of the economy was textile industries, handicrafts and agriculture. Sheep breeding was one of the major occupations of the people which gave a boost to the textile industry. There was seasonal migration of people in winter mainly to save them from the difficult cold weather and also to sell their textiles in the market.

The area was highly populated and the over-grazing and human interference affected the forest severely and caused large scale erosion during 15<sup>th</sup> and 16<sup>th</sup> centuries. Many laws were passed for protective measures and a large scale reforestation process took place in mid 19<sup>th</sup> century. National routes were opened up and area got access to the neighbouring valleys. This happened in the end of 19<sup>th</sup> century which also caused the huge emigration of the people to Mexico mainly for business. It is interesting to note that during this time i.e., in 1836 the population was recorded to be 14846 which was depopulated to 6350 in 1968 and only 3000 people were the inhabitants of Barcelonnette (Weber, 1994).

The present day economy no longer depends on agriculture and farming alone but the stronghold has been gained by tourism activities (winter sports and summer leisure activities) Barcelonnette earns most of its profits from it (INSEE, 2009). It has the oldest winter ski resort in France. Since 1970s tourism has been the major source of activity in the area. It earns about 10% of the total GDP of the Provence (INSEE, 2009). The next section has been dedicated to tourism activities to elaborate its importance in the economy.

There has been large scale development for attracting tourists in the area. There were several activities like widening of the existing roads and construction of new ones, excess irrigation in slopes, ski-resort installation by slope cutting and terracing as well as building hiking tracks has negative impact on the stability of the slope.

#### **3.6.1. Economy And Tourism**

The mainstay of the economy in this area depends on tourism. The tourism activity of the PACA (Provence-Alpes-Côte d'Azur) is the second largest in France (INSEE, 2009). Many measures have been taken to preserve the environment and develop a sustainable touristic activity in the area. Tourism accounts for about 10% of the GDP of the entire PACA. In spite of the economic crisis during 2008 there was decline in total hotel occupancy by 1% (INSEE, 2009) in all other regions within the PACA except for the mountain region. Among the 40000 beds available in the entire Ubaye valley a large concentration of these accommodations are located in the Barcelonnette town.

Tourism has been either directly or indirectly acting as a job generator in the area. About 70% of the total people involved in this area are dependent on tourism (INSEE, 2009). Not only shops and small business activities but also ski lifting, ski instructions, accommodations are the highly dependent to tourism.



## 4. Materials And Methods

This chapter focuses on the assessment of the data that was available and had been collected from the field. A brief description of the fieldwork had been included and the final available data used for the study had been described.

The work outlined in the preceding pages had been made possible mainly due to the availability of various primary and secondary datasets to analyze, compare and validate the results. It was also necessary to investigate the gaps in the existing data and gather the required information during the field work phase.

Furthermore the methodologies adopted for achieving the final objective are described in this chapter. Based on the literature review in chapter 3 the methodology for the assessment of flood risk in the area described both pre and post processing of the available data.

### 4.1. Overall Methodology

The methodology of the study is divided into four major stages. The first stage was scanning through the available database and identification of the required data or gaps within the data. A detailed investigation through the available database was done in order to identify what was already available and what was required for the analysis. This stage corresponds to the fieldwork that what had to be collected in the field.

The second stage dealt with the data collection in the field and then preparation of the data for modeling and analysis purposes. The data collection was done for validation of the existing database and measurements were taken to acquire what was absent in the database. The elements at risk, the physical factors and the man made terrains were identified in the field for further analysis of the results from the model.

The third stage entailed modeling of the flood event for different scenarios and validating the result using ground truthing and historical data. This stage also involved the assessment of the suitability of the model in terms of sensitivity of the results with reference to different levels of uncertainty. For modeling, data collected from the field were used and calibration and validation was done based on the field measurements. The modeling of the flood provided the extension, depth and duration for the different return periods and scenarios were generated for them. This assisted in the hazard assessment.

The final stage of the study dealt exclusively with detailed analysis of the results obtained from the model and impact assessment on the different elements at risk. This also included calculation of the level of risk and vulnerability in physical and economic terms. The assessment was also done based on analysis of the inundation events historically and also if such an event occurs in the future then what will be the risk consequences. Figure 4.1 indicates the schematic flow of the overall research process.

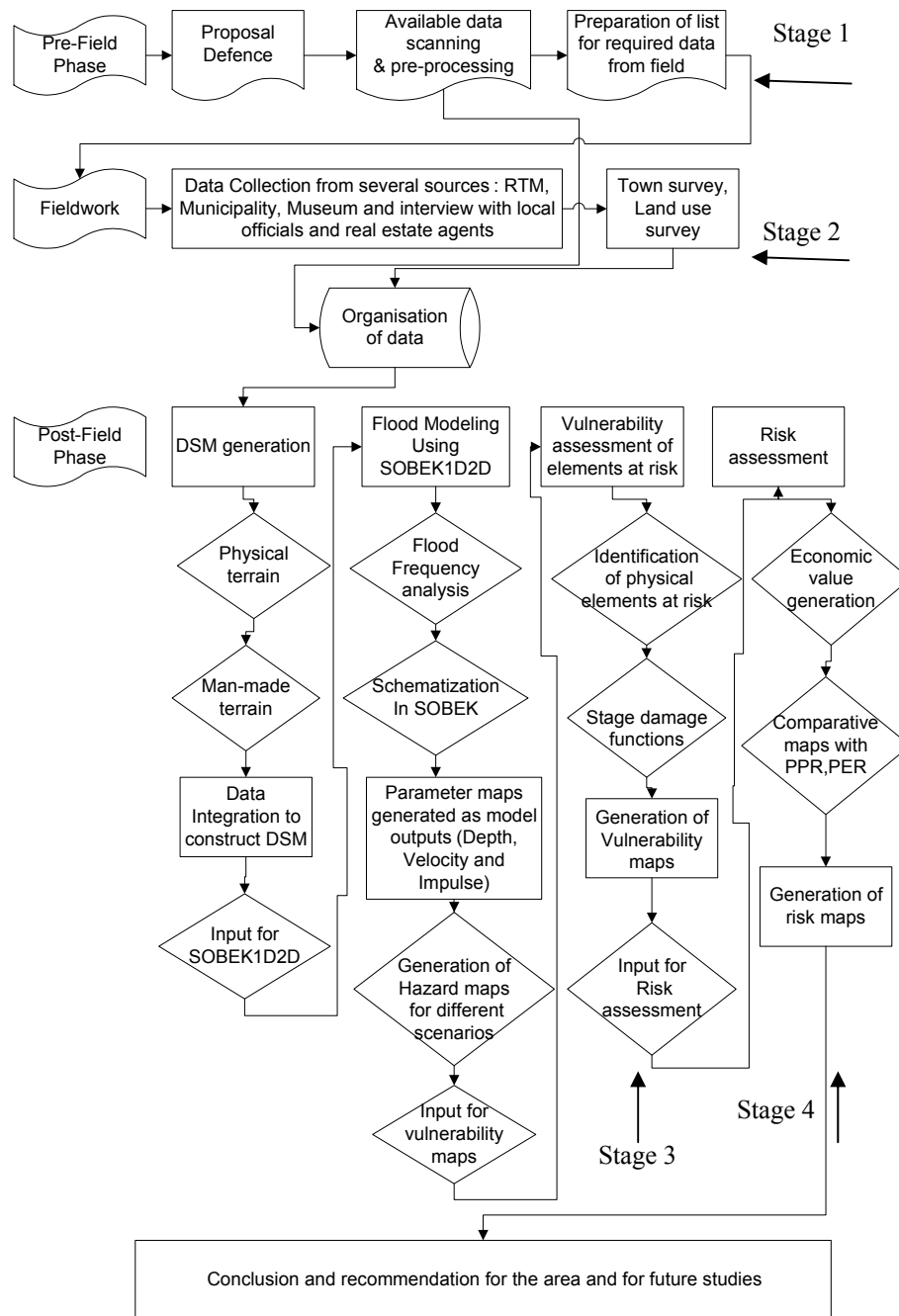


Figure.4. 1.Schematic flow of the overall research process

#### 4.2. Available Dataset

The available data sets were divided into the following sections depending upon their contents. They are listed in Table 4.1.

**Table.4. 1.**Shows the data used in the research

S.No.	Type of Data	Source	Description
1.	Topographical map	Directorate of topographic survey, France	Number XXXV 39 1 and 2,1963 Scale:1:25000
2.	Aerial Photograph	Archive	Year - 2004 Resolution- 0.5X0.5m
3.	Land cover maps	Archive and validated	Year-2008, scale-1:10000
4.	Meteorological Data	Meteo-France station, Barcelonnette	Temperature-1963-2002 Precipitation- 1904-2009 Snow depth – 1995-2005
5.	Discharge data	Abattoir discharge measurement station,Barcelonnette, the Ubaye River	1904-2009
6.	Geology/Geomorphology	Existing literature	D.Weber (1994)
7.	Official risk maps	RTM and Municipality	PPR (Prévention des Risques naturels prévisibles) and PER (Plan d'Exposition aux Risques)

#### 4.3. Dataset Required

After examining the available data and past studies the analysis for the required data began. It was obvious that not all the data for the completion of the study was available necessitating the need for a field trip to the area for three weeks to collect the missing data.

The main focus of the study was assessment of flood risk from the past flood events and investigate their impacts on future scenarios. Therefore it was necessary to gather data for both past and present situations. There was lack of continuous meteorological data like the rainfall and the temperature data which were later obtained from the meteorological department though not for the whole time period i.e., the temperature data since 2002. Data for the calibration and validation of the model results of the two major events (1957 and 2008) were required. These were generally in the form of flood depth and duration of the events.

For risk assessment it was necessary to have a detailed and updated version of the elements at risk, in this case the physical elements. This also required some existing risk assessment and preventive measure maps for a comparative study. Evaluation of the exposed elements at risks with the present economic condition needed values of the elements, which were obtained from detailed survey during the field work.

#### **4.4. Data Collection**

The fieldwork focused on collection of data related to the hydrological regime of the area and past inundation events. These data were scattered in various organizations like the RTM, local municipality and the museums. Furthermore electronic version of the reports and some data layers like the risk map and the local PPR were collected from the local municipality. Most of the official data were in French and required translation. Valuable insights were also gained from the knowledge of the local people working in these organizations.

##### **4.4.1. Past Inundation Events**

Data collections for the past events were mainly based on the statements, technical reports, expert views and local decrees by disaster management departments and agencies working for decision making bodies. They also included regional newspapers. This was performed by visiting various administrative offices such as the local municipality (Town hall) and the RTM (Service de Restauration des Terrains de Montage- Mountain Land Restoration Service). Information found in the local newspapers were also included.

The major regional flood event in Barcelonnette occurred in 1957 and since it was an old event there were not many facts that were available. Some old records such as PhD thesis by Le-Carpentier (Lecarpentier, 1963) and report of Dr.J.Tricart are the major sources of information. Information of the specific climatic characteristics that triggered the event were available from report by Dr. J.Tricart (Tricart, 1958) These records including some other old records were however more descriptive in nature.

Personal communication and interview with Mr. Michel Peyron (an executive in RTM) revealed some more information about the flood extent and some field photographs of the event threw light on the depth of the flood water. Even the total discharge data for the event in 1957 was not available directly from the L'Ubaye Abattoir station in Barcelonnette as the measuring scale was broken during the flood

and there was a gap in the dataset following this event. The approximation of the discharge data was done from different reports and literature available from that time.

In case of the event in 2008 there was more data and information available Newspaper reports for day to day condition of the event and other documents like reviews and articles as well as verbal communication with local officials provided a lot of information about the event. A complete series of data for water depth at the time of event for a particular point (Abattoir) was available for calibration of the model.

#### **4.4.2. Land-Use and Land-Cover Changes**

As discussed in section 4.2 land cover map for the study area was available, but required validation and updating, because it was necessary to ascertain whether the area had gone through any drastic change in terms of developmental activities and the kind of changes that took place during the last one year since 2008. A survey of the different land-use classes was made and any changes in or any new additions were made to update the available database. There were a few changes that occurred in the last one year. Some new constructions and protective measures in repairing and increasing the height of the dyke in certain areas for safety from future floods were included in the database of infrastructures for protective measures.

#### **4.4.3. Town Survey**

To investigate the elements at risk from flood hazard a detailed survey was made to identify their locations and condition. The central focus was towards the physical elements which were affected by past flood events and can be affected in case of future extreme event. Therefore the survey included not only the area in and around the Ubaye River but also those which may be affected in times of large events. Survey of areas higher up in the slope was done in order to identify areas which will be safe during such events for sheltering people for evacuation purposes.

The survey mapped the physical elements (buildings and infrastructures) such as their functions, material of construction, and condition at present and essential facilities available. Major infrastructures and essential amenities for example hospitals, fire stations and police stations were also identified for quick evacuation and relief purposes. New plans of development like increasing the height of the dyke and maintaining the existing system of flood protection measures were discussed with the municipal officials and their perception of the issue of flooding was gathered verbally.

#### **4.4.4. Official Risk Map and Prevention Plans**

The local risk protection authority RTM in combination with the Municipality had prepared maps for risk assessment based on multiple natural hazards for the region. They were collected during the field from the local municipality. They gave an insight of the type of protection work that has been carried out based on these maps. Repairing and maintenance of the dykes and embankments, reforestation of the

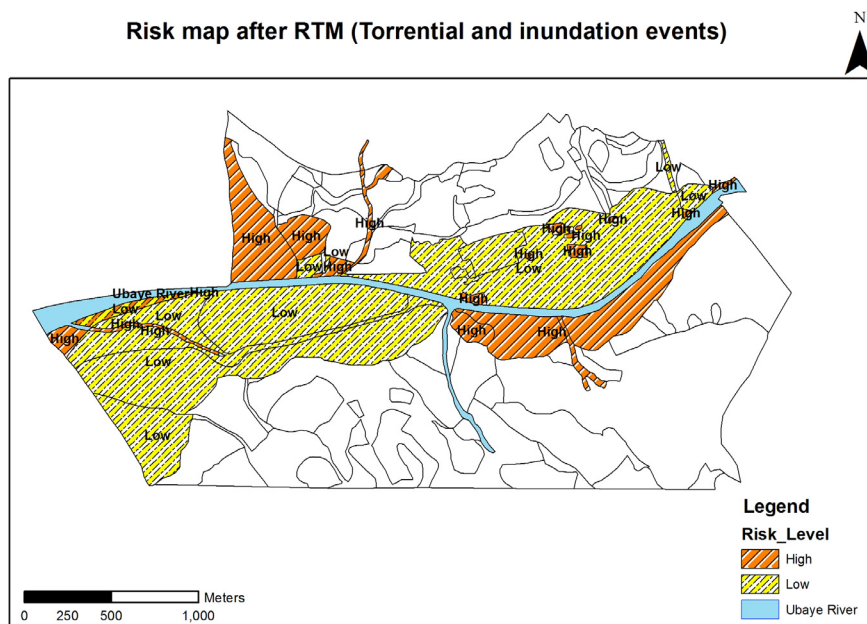


Figure 4. 2. Risk map based on inundation and torrential events identified by RTM

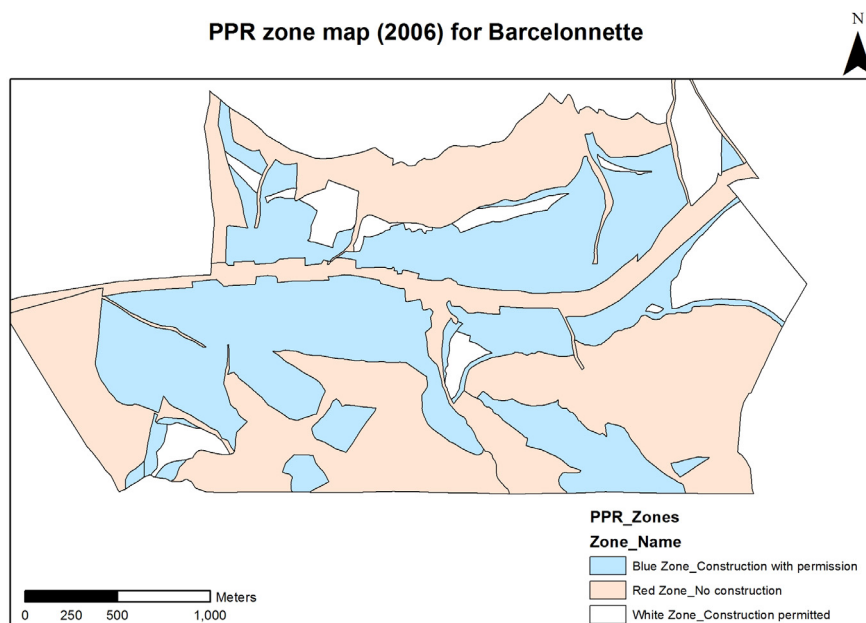


Figure.4. 3. The PPR for Barcelonnette Urban area including the location of buildings (2006)

slopes, maintenance of check dams upstream and plans for building new bridges are the major protection activities that are based on these risk maps.

The maps were based on multi-hazard criteria such as landslides, debris flow, and inundation, mudslides. The methodology adopted for the generation of the risk maps were based on qualitative approaches. Communication with the RTM official revealed that the basis of flood risk assessment were the capacity of the bridges on River Ubaye to pass water through them, the mass movement caused by the torrent in La-vallette, houses at the upper slopes at risks and experts views. The area was divided into low, medium and high risk zones based on the intensity of probability of risks in this area. The map is (Fig.4.2) showing the risk zones as a result of torrential activities and inundations identified by RTM. Two zones were identified as affected by torrential and inundation activities for example the high risk zone and the low risk zone.

Based on the risk maps the plans for protection were prepared by the RTM. The major hazards concerned are the flooding, ground movement, earthquakes, avalanches and wildfires (INSEE, 2009). Plans for safeguarding the local people from hazard were also prepared but up to date they have not been approved officially till now and further modifications are being done. It is expected that a new Plan Communal de Sauvegarde (PCS) will be published in year 2010.

The first type of plan for protection from natural hazards were formulated as PER (Plan d'Exposition aux Risques) available since 1985. Since the year 1995 PPR (Prevention des Risqué naturels prévisibles) (Fig.4.3) was implemented with the intention of protecting development in areas where the level of risk is highest. These plans divided the township into several zones accommodating those areas with high risk in red zone, medium risk in blue zone and meager or no risk in white zone. This in turn also meant that those colors identify the criteria for development under different zones. Those under red zone will be denied permission to develop any kind of new infrastructure within their limits while those in the white zones have full permission for development, whereas in the blue zone development will be done only with special permission.

#### **4.5. Methodology: Data Preparation**

The available data were organized and processed for the analysis. The quality of the data was analyzed to identify any kind of abnormalities such as very extreme values. The goodness of fit of data was evaluated with several statistical models and at the end Gumbel's max statistical model was selected for further analysis. Descriptive statistical analysis was conducted to see the distribution of the data. The analysis is further explained in section 5.3.1.

Lambert conformal conic projection system was used. The satellite imageries and topographic maps were rectified and geo-referenced. The estimations were performed in metric projection system.

#### **4.5.1. Climatic Data Analysis**

The typical characteristics of the climatic regime in the Barcelonnette area as discussed in section 3.2 which intrigues to look deeper into the climatic parameters such as temperature, rainfall and snowfall since their behavior have a great impact on the geomorphologic behavior of the unstable landmass on the slopes, torrents and streams. The climatic factors such as rainfall, temperature and snowfall were therefore compared using representative histograms and the resultant effects on the discharge value were observed. The complete series of maximum daily temperatures were averaged for monthly temperature and further averaged to one value per month for the entire series of data. This data are then graphically analyzed. Similarly precipitation data for every month were also analyzed and plotted in a graph. It indicated the seasonal variation in the area to have an understanding of the climatic situation of the area. Further explanation can be obtained about the results from this analysis in section 5.1.

#### **4.5.2. Probability Analysis**

Previous studies as discussed in section 2.2 have identified (Nash and Sutcliffe, 1970) that statistical methods should be applied to conclude for flood probability analysis. This can be established from parameters such as rainfall or water height used for deriving discharge data. It was therefore necessary to evaluate the distribution of the available data and the probability of the occurrence of flood events (Calver et al., 2009). For this, a Gumbel plot is one of the most widely used statistical measures (Robson, 1999) for such kind of calculation and it was applied to get the probability values of the occurrence of extreme events. This also calculates the different return periods for flood modeling. The results for this analysis can be found in section 5.3.1.

#### **4.5.3. Generation of DSM**

As described in sections 2.4.1 and 2.4.2 the analysis of realistic terrain surface generation depends on three major factors:

- The accuracy and distribution of the elevation points used for DEM generation
- The selection of proper algorithm for interpolation and
- The choice of appropriate grid cell size.

Based on these criteria the following methodology was adopted to generate the DSM as an input for the flood modelling. The resolution was selected as 10 m based on the literature (Maune, 2007),(Rahman, 2006),(Tennakoon, 2004) where it had been indicated that for hydrological modeling a DEM resolution between 7.5m to 20 m gives the optimum results (Kienzle, 2004).



#### **4.5.3.1. Natural Terrain**

The natural terrain deals with the elevation data representing the topography and the river channel. The first stage of DSM generation was for hydrological modelling needed for hydrologically corrected surface. Therefore generation of surface from contour map is made from digitized contours from (topographical sheet number XXXV 39-1 and 2) of the area of 1:25000 scale published by Geographical Section, War office 1943.

Topo to Raster function in Arc GIS was used to create the surface based on the principle of ANUDEM (Australian National University Digital Elevation Model). This was because the interpolation method here is specifically designed to create DEM's for modeling hydrological parameters. It interpolates the raster surface in such a way that the general constraints for hydrological modeling like a non-connected drainage structure and incorrect representation of ridges and streams from input contour data are minimized (Hutchinson, 1996). This gives a realistic representation of the surface. The elevation values were represented in the form of float values so that there are no sharp changes in the values if it was not present on the surface. ANUDEM uses an iterative way of finite difference interpolation method (ESRI, 2009). It incorporates both the advantages of global and local interpolation methods together by calculating the grid in successively finer resolutions. The imperfections in the elevation data were further reduced by using the technique of fill sinks from the hydrology module of Arc-GIS. A surface was created with 10x10 cell resolution as an input for further analysis.

The river bathymetry data collected from the field were incorporated in the DEM for accurate representation of the topography.

#### **4.5.3.2. Man Made Terrain**

The manmade structures such as the buildings, infrastructures, dykes and embankments, bridges, roads and past and present developmental activities were incorporated within the man-made terrain features. The building heights were added to the terrain while two sets of manmade terrain surfaces were created for the dykes; one with the elevated height preceding the flood prevention measures after 1957 event and one before that and separately incorporated in. All the layers are rasterized and the spatial analyst module of Arc-GIS is used to add the data value to them. The integration of the data created for natural terrain and man-made terrain was performed in Arc-GIS by using the spatial analyst raster calculator tool.

The results for the generation of DSM through integration of the two kinds of terrain discussed above can be obtained in section 5.2.2.

### **4.6. Flood Modeling**

For comprehensive flood risk assessment the estimation of hazard and the consequences of flooding is essential. The selection is mostly made on need based and/or data based. For modeling the flood hazard SOBEK1D2D model was selected which allows the computation of both one dimensional channel flow and two dimensional overland flow modeling. The characteristics of the model can be found in details in section 2.3 of literature review chapter.

#### 4.6.1. Boundary Conditions

“The boundary conditions describes the exchange of water mass between the study area and the rest of the universe during the model run” (Alkema, 2007). In order to do so it was necessary to have appropriate measurement of water entering and leaving the area. The boundary conditions for the model are set based on specific return periods (refer to section 4.5.2). The data for 75,150,225 and 500 years of return period and their corresponding discharge values were calculated.

Two boundaries were set up as upstream and downstream boundary. The upstream boundary of the model uses the discharge data as input. The discharge data for the model were obtained from the measurement station in Abattoir in Barcelonnette. For 2008 event the available rating curve was used to derive the discharge data on an hourly basis. This was done in order to have parity between the available hourly observed water height data which were later used for validation of the event as described in section 5.3.4. The fig.4.4 Shows the rating curve for 2008 which was used to derive the discharge values.

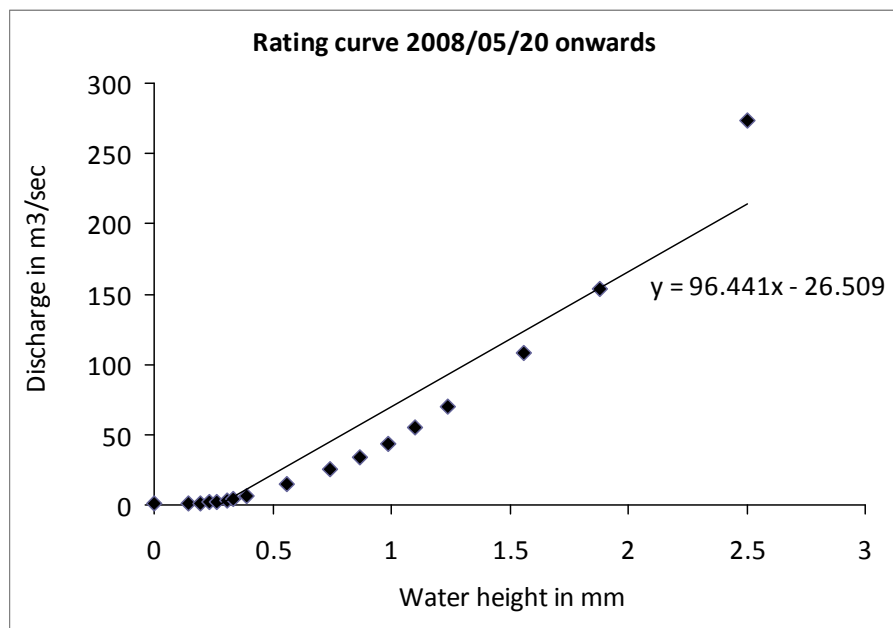


Figure.4. 4 Graph showing Rating curve and rating equation for 2008 event

The upstream boundary consists of a time-series of discharge data. The lower boundary or the downstream boundary consisted of an imaginary lake condition which is set to have a water holding capacity of up to two meters from its immediate value of elevation. To preserve the lake condition a constant water level was specified and a free flow was allowed throughout the simulation.

Surface roughness values are the most important aspect of sensitivity analysis of flood models. The roughness values (wall roughness and bed roughness) were used for sensitivity analysis of flood model. The values were assigned derived from Mannings coefficient (Chow, 1959) depending on landuse map. For details refer to literature review section 2.3.4.

#### 4.6.2. Model Building: Schematization

The model 1D2D SOBEK was schematized to get appropriate outputs for flood hazard assessment. The initial values for the event were used in the settings e.g., date, duration, initial water level and the interval with which the output maps will be generated. The combined channel flow and overland flow module of the SOBEK was used with a selection of un-steady calculation. The network editor is the module available in SOBEK to schematize the model. The NETTER (Network editor in SOBEK) allows schematization using vector layers as references. The two modules 1D and 2D have different requirements of inputs for processing. The inputs for the overland flow module (2D) were the already generated DSM and the friction map while the channel flow module demanded the river cross sections, calculation points, boundary nodes and connection nodes. A typical example of model schematization has been illustrated by the figure (Fig.4.6).

A number of history stations were also incorporated to contain the 2D results at a specific pixel. Several cross sections along the river were specified to estimate the bathymetry of the river. The four bridges in the area are included in the schema and measurements according to the field data are integrated. The surface roughness (friction) values were used to analyse data for grid and providing the appropriate value and calibrate the model to get an optimum result. The final results for the sensitivity analysis of the model performance can be seen in section 5.3.3 .



Figure.4. 5. River cross section input and data edit window

Initial condition of the model was adjusted to the rivers hydrodynamic behaviour by running some test simulations and reaching at a level where the normal condition of the River persists. This condition was preserved in the form of RESTART files which were used for the next run of the model for future simulations. The cross sections are fed in the model in the form of trapezium values with corresponding

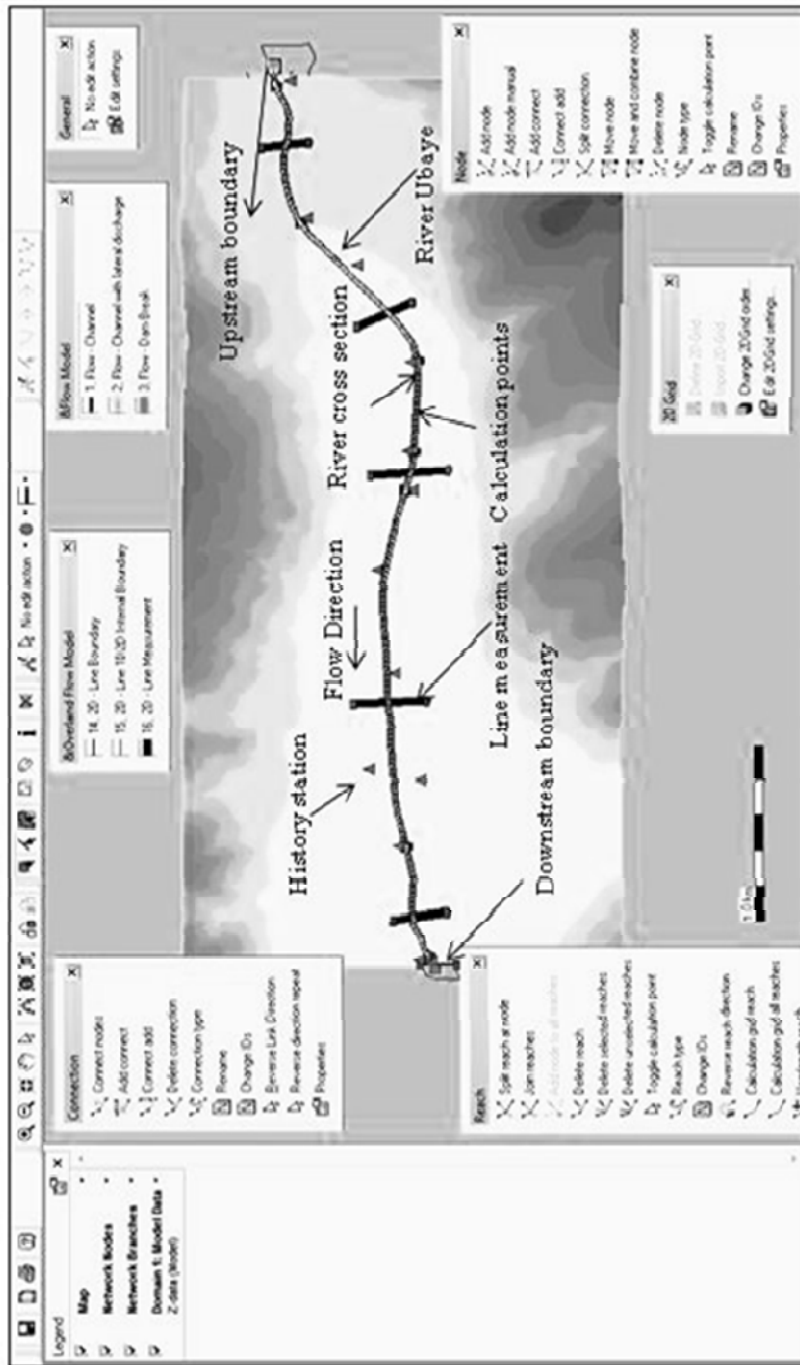


Figure 4.6. SOBEK1D2D Model Schematization Phase

flow width and bottom width values. The figure shows the input window for the delineation of cross sections in SOBEK (Fig.4.5).

The course of the river is identified by the reaches which have been further joined by the connection nodes. The interpolation of the river bed and the water flow is done by the model itself based on the cross section values assigned to the model. Therefore it is very important to define them accurately. Here in our study the trapezium

#### **4.7. Generation of parameter maps**

The result from the model was in the form of flood characteristics maps. Additional information about the flow characteristics of the river were obtained from these maps. They are maximum depth, maximum velocity and maximum impulse maps.

1. Maximum water depth (unit in m): This flood characteristic map indicated the maximum depth of water which occurred during an event. This map is very important for identifying potential areas which were affected by highest depth of water and influence the elements at risk in the area. It clearly denoted the amount of potential damage for a given area for a particular return period.

2. Maximum velocity maps (unit m/sec): These parameter maps indicated the maximum velocity of the flood water per unit of time. This component of flood characteristics is essential for hazard identification since it is an essential parameter for identifying degree of damage. It is interesting to note that sometimes large amount of water with lower velocity causes much less damage than a smaller amount of water with higher velocity.

3. Maximum impulse (unit  $m^2/sec$ ) : It was very important to know both the factors i.e., the flood water depth and the velocity. Therefore the impulse maps (which were the product of water depth and velocity of water) were used for further analysis in hazard mapping

The model outputs were converted to usable formats in Arc-GIS and classified based on their values. The results for this section can be obtained in section 5.3.2.2

#### **4.8. Hazard assessment**

Hazard assessment was performed using the parameter maps by calculating the annual probability of occurrence of any event of specific return period. The areas affected by the flood parameter maps in terms of depth, velocity and impulse were identified and mapped in a 0-1 scale of damage and their annual probability of occurrence. This satisfies the fact that the “event has a probability of occurrence within a specified period and within a given area and has a given intensity” (Geohazards, 2009) explained in details in section 2.5. The resultant flood hazard map for different return periods can be seen in section 5.3.2.2.

#### **4.9. Vulnerability Assessment**

The first step in vulnerability assessment of the physical infrastructure holds to the identification of the elements that are at risks as describes in section 2.6 of literature review. The identified physical elements were then classified as shown in the Figure

4.7. Based on the town survey the tangible elements at risks were identified and updated in the existing database. A detailed survey was conducted to identify the infrastructures, essential facilities and the transport facilities.

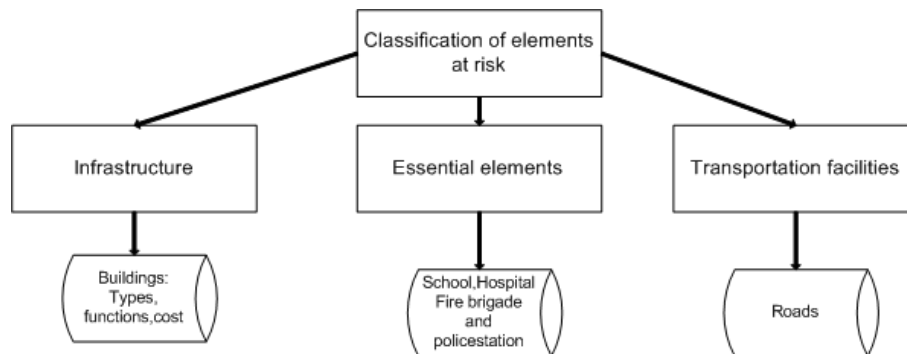


Figure.4. 7. Schematic diagram for identification of the physical elements at risks

Individual buildings database was filled with attributes based on their type, condition and material of construction. Essential facilities were identified and located on the map. Separate theme maps were generated for land use, buildings, essential amenities, roads etc (appendix 3). The exposure characteristics (factors affecting the vulnerability of the elements at risks) and the severity of inundation (flood characteristics) were investigated using several GIS operations like overlaying and raster calculations and the affected units (physical infrastructures) were identified (refer to Fig.6.2).

The stage damage functions were identifying the total rate of damage at different levels. The damage functions for United Kingdom, Germany and France were used to assess the vulnerability of the elements. The damage functions were associated with flood depth and vulnerability curves. A new flood vulnerability curve specific for the study was generated to use for risk assessment. Furthermore, detailed database were associated with each of these theme maps and were used for risk assessment (section 6.4).

#### 4.10. Risk Assessment And Economic Value Generation

Two types of risk assessment were performed for this study. The qualitative risk assessment and quantitative risk assessment. As already described in the literature review section 2.7 that qualitative assessment of risk was based on experience and expert knowledge and the risk areas were classified into low, medium, high and very high classes. The condition taken to identify risk zones were based on the level of hazard intensity and rate of vulnerability of elements. The vulnerable elements in this case were the land use classes. They were given a weight according to their level of importance. This was done for the land use classes since no data for value of the land uses were available.

Quantitative assessment of risk was also performed mainly for the buildings since they were the only elements whose values in monetary terms were known.

It quantified the risk according to the following equation:

$$\text{Risk} = \text{Hazard} * \text{Vulnerability} * \text{Amount of Elements at risk}$$

(Geohazards, 2009)

The risk assessment was done for the buildings and other infrastructures since the value for these elements were collected from the field through various real estate agents and statistics from DDA (District development authority) during fieldwork. The risk was expressed in monetary terms. The preliminary economic damage assessment was based on the intensity of hazard and rate of associated vulnerability to the buildings and physical infrastructures for the return periods 225 and 500 years. Moreover an assumption based estimation of total economic damage was also made in case of total destruction of all the elements at risk for instance in a 1000 year event. This was performed in order to get estimation for the local authorities to ensure insurance against flood risk for the area for the next 1000 years. The values of the assets (buildings in this case) were classified into broad categories based on their types. The economic value of the physical elements of risks were estimated using the value obtained from the local real estate agents and the DDA statistics published by the Jausier municipality for the year 2002 and rates were adjusted to the recent rates. The evaluation of the economic value of the elements and the probability of occurrence of the events were used to estimate annual risk. For detailed analysis refer to section 6.6.

The specific risk of the elements was identified annually as a consequence of flood hazard for specific return periods in the form of risk curve. The risk curve was generated for getting average annual risk potential for up to 1000 years. This in term was done by spatial probability and cost of damage per building type. They were aggregated together to express the total risk in the area with reference to flood hazard at a given time.

The risk zones were categorized based on high, moderate and low risk. The classes were fixed based on the magnitude of hazard, probability of occurrence and the vulnerability of the elements. The comparison with the RTM risk maps and the final risk map was further analyzed to see the correspondence between the generated map and the existing map for e.g., risk maps, PPR and PER zone maps.





## 5. Data Analysis and Hazard Assessment

This chapter is devoted to the discussion of results. This also describes systematically the significance of the results based on the methodology described in chapter 4. Research questions were addressed to reach the specific research objectives and further continued through the following chapter 6 to reach the final goal of the research.

### 5.1. Climatic Factors And Their Effects

For accurate evaluation of the flood situation it is necessary to know the factors that have actually triggered the event. Climatic parameters are one of the most important natural triggering factor for a flood event. Therefore, it was decided to look into the climatic parameters briefly based on the available data. On the basis of regular observation of the National Meteorological Department in France, certain atmospheric phenomenon were studied to see the normal trend of these observable facts and if there were any drastic changes in their normal condition in the past few decades. Although there were existences of certain over estimation or under estimation of data during the major events, the available range of data was able to provide a general idea about the weather condition in the area. The variability in rainfall and temperature in the area has a great impact on the geomorpho-dynamic behavior of the unstable landmass.

#### 5.1.1. Temperature

The study area as described earlier in section 4.2 has a dataset for temperature from 1961-2002 with a gap from 1994-96. It was analyzed to see the temperature trend in the past few decades by plotting the maximum and minimum temperatures for each year and then comparing it with the 5years moving average (Fig.5.1).

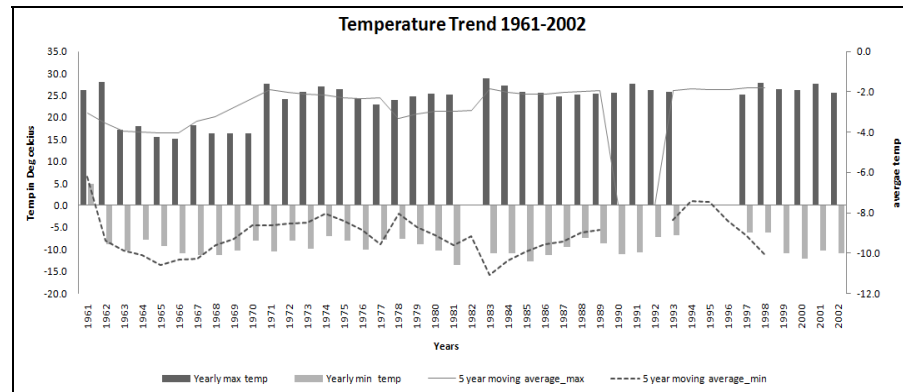


Figure 5. 1.Graph showing the trend of temperature from 1961-2002 and its relation with 5 years average

The readings for the temperatures were taken from the Barcelonnette observation station (1440m) and relates mainly to the bottom of the valley. In general it was observed that it varies considerably based on altitude and direction of slopes. There was a sharp difference (about 9degree) between the average maximum temperature difference between 1960-70.

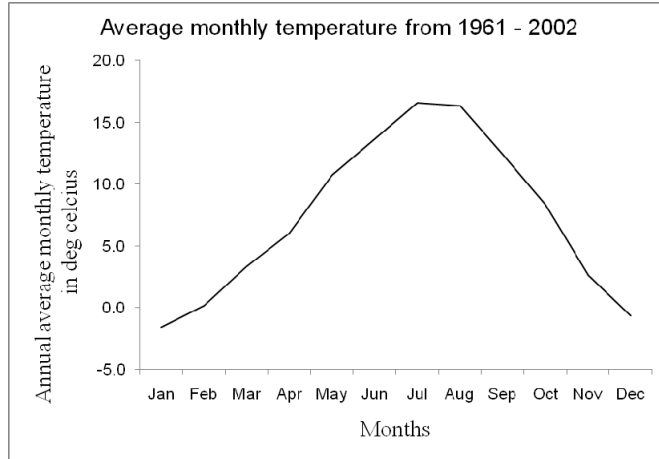


Figure 5. 2. Temperature distribution from 1961-2002 on an average annual monthly basis

The averages of all the months were then plotted for all the years (Fig.5.2) .The temperature in the valley floor showing a consistency in the average values. There may be some discrepancies in conclusion because average temperatures are considered to over ride minor daily deviations.

### 5.1.2. Precipitation

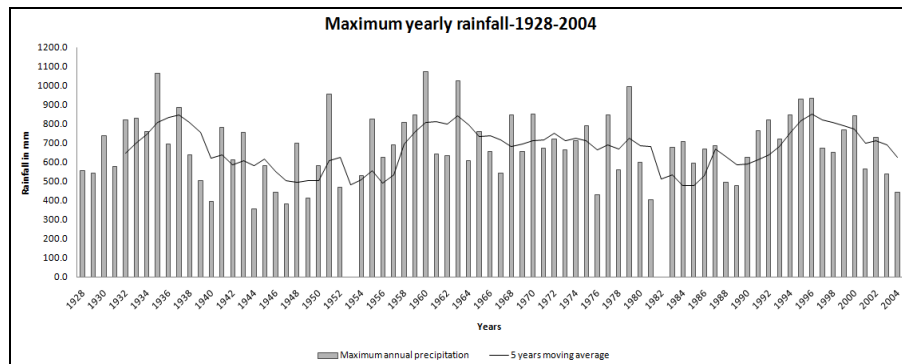


Figure 5. 3. Graph showing precipitation trend and its relation with the 5 years moving average.

The data for rainfall distribution (Fig.5.2) was plotted in a histogram to that even low amount of rainfall may cause accelerated earth processes because of the morphology of the area. In June 1957 the regional level disaster occurred due to 105mm of rainfall occurring in three days and a high speed melting of snow in the higher slopes. It was also accompanied by numerous other small flows and torrential flows which partly blocked the Ubaye River (Weber, 1994). Spring and autumn being the wettest months complimented by the summer storm showers in general but it is difficult to conclude any specific outstanding rainfall situations within a day from these monthly average values. Temporal variability can be observed year to year. There was a general oscillation in precipitation amount every 20 years.

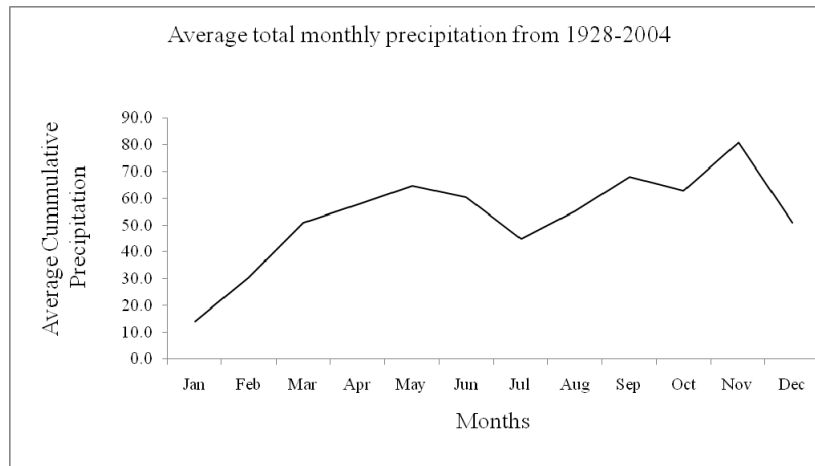


Figure 5. 4. Average Total monthly distribution of precipitation from 1928-2004

The plot of average total precipitation in Fig.5.4 indicates that there are two definite peaks in rainfall in a year one during May-June and the other during November. The data also reflects the rainfall regime of the area but makes it insufficient for the reason that the analysis is based on average rainfall. This sometimes conceals the impact of exceptional rainfalls. Spatial variability is also an important aspect to consider in the higher slopes as the amount of rainfall recorded depends on the local winds, the orientation of the slopes and the topography of the observation station.

### 5.1.3. Snowfall and Wind

The snow depth observations for 11 (1995-2005) years time period was obtained at the Restofond pass at an altitude of 2720 m, north facing slope. There are other factors which affect the depth of snow at this altitude like air temperature, wind direction and wind velocity. An average of 1.3 meters snow fall is recorded in the Barcelonnette area in the valley region while it reaches up to 8 meters in the ski-ing area at about 2500-3000 m high on the shady southern slopes(Weber, 1994) .It stay covered for at least 4 to 5 months in a year.

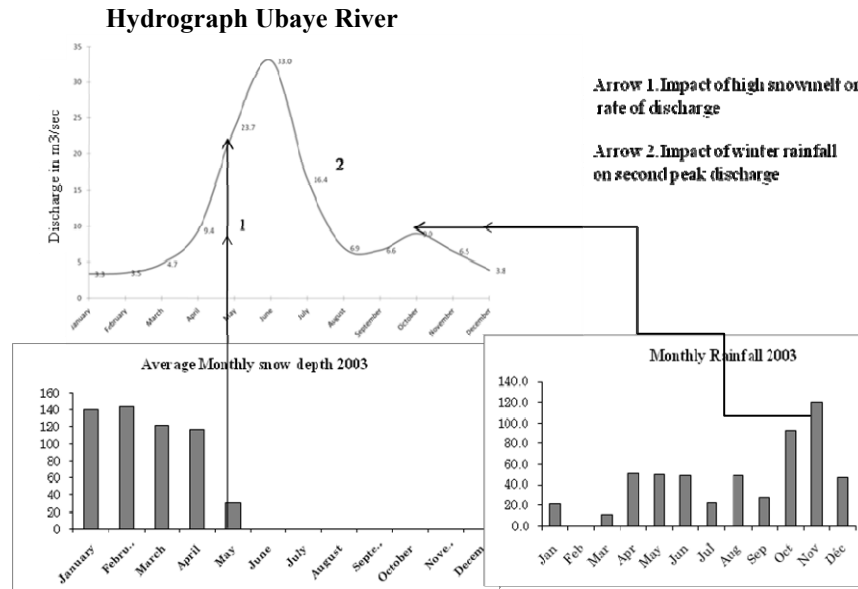


Figure 5. Relationship between snowmelt, rainfall and discharge for Ubaye

During the summer the rate of snowmelt has a direct impact on the rivers peak discharge. In the event years (both 1957 and 2008) the rate of snowmelt had been higher than the normal years. The Fig.5.3 suffice the point that snow melt has a large impact on the Ubaye River’s hydrological regime especially in summer.

According to the local people there has been neither any decline in the amount of snowfall nor are there more frequent wetter winters and drier summers as a possible indication of climate change in the area. There has been very little regional differences in rainfall otherwise higher peaks in rainfall causing higher peaks in river discharge are quite normal and not major issue of concern for the area with few exceptions during the event years.

#### 5.1.4. Hydrology: Discharge

The Ubaye River can be hydrologically defined as a “nivo-pluvial” regime (Weber, 1994) i.e., it shows two distinct peaks in its hydrological regime . Based on the available discharge data it was noticed that the low water period of the river is during December to March while the high water season is from April to June as a concentrated effect of rainfall and snowmelt together. During October there is another peak because of autumn rainfall. The various streams that are contributing to the main river are torrential in nature and the seasonal torrentiality of Ubaye can be attributed to the pattern of rainfall in the area. This also results in high rate of erosion and accumulation of debris and sediments downstream in the Ubaye flood plain.

Torrential flows occur generally during May to November with the peak during July while spring flood arise due to excess rainfall and higher rate of snow melt. The autumn floods are more dangerous in nature because there are chances of occurrence of flash floods.

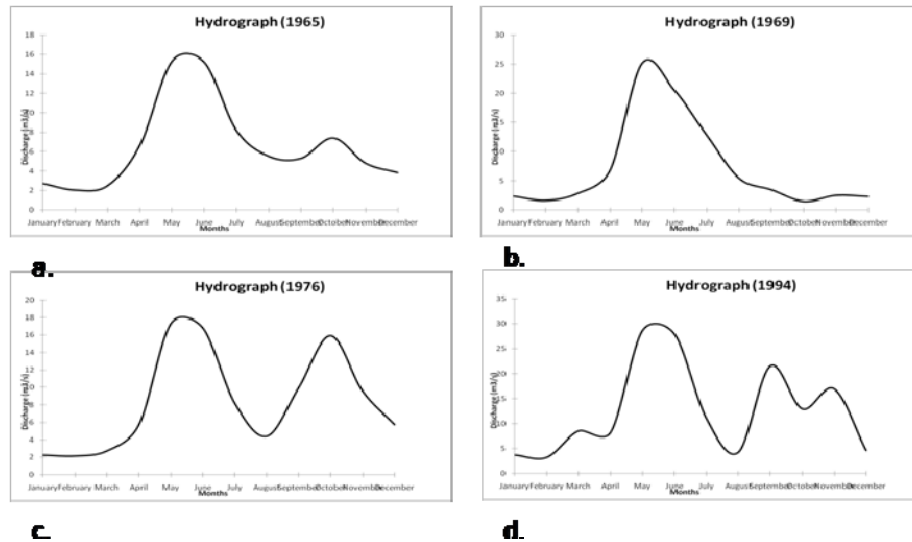


Figure 5. 6.a.) Hydrograph 1965: Normal Flow regime of Ubaye  
 b.) Hydrograph 1969: Flow regime with low winter rainfall  
 c.) Hydrograph 1976: Dual peaks with high discharge both in summer and spring  
 d.) Hydrograph 1994: Rare case of three peaks with high discharge

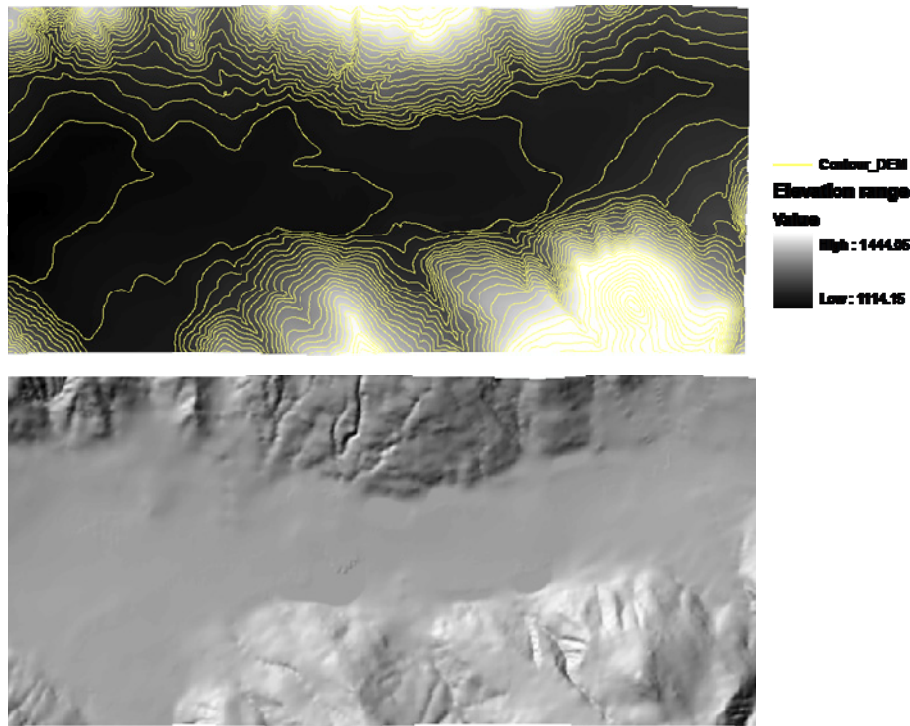
The four graphs (Fig.5.9.a, b, c, d) exemplify the behavior of the hydrological regime of river Ubaye. They show the four different types of hydrographs chosen from several years to show how the factors like variability in rainfall and snowfall has an impact on the hydrological regime of the river especially in summer. Thus it can be concluded that the climatic factors have a major hand in triggering events which might lead to disasters. A better understanding of these issues can help in assessing the natural system and its activities in the region in an improved way.

## 5.2. Generation of Digital Surface Model (DSM)

Generation of a digital surface model was the foremost objective of the study. The technicalities and the difficulties during the generation of the surface are described below based on the methodology described earlier in section 4.5.3.

### 5.2.1. Natural Terrain and Manmade Terrain

A hydrologically corrected DSM was generated with a resolution of 10m based on literature as described in section 4.5.3.1



*Figure 5. 7. Contour overlaid DTM and Hill shade generation for visual assessment of the surface.*

Two separate DSM's were produced for reconstruction of the flood events before dyke height increase in 1957 and after the protection measures were carried out and the dyke was increased in height by 0.5 m. The new DSM was used for construction of the near flood event of 2008.

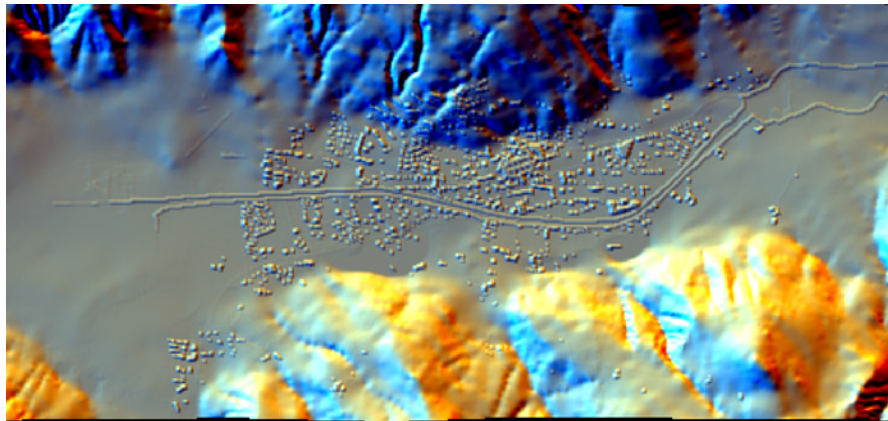
Due to the non-availability of field elevation data it was not possible to make any mathematical calculation for DTM accuracy assessment. However, alternatively visual interpretation through contour overlaying and hill-shade analysis was done to check if there were any unwanted pits or sinks in the surface. The Fig 5.7 illustrates a visual assessment of the accuracy of the DEM generated in case of existence of any un-natural or erroneous sinks by overlaying the representative contours and the generated surface. Moreover with the help of the hydrology tool in ARC-GIS the flow path generation and pour point test was performed to check for any un-natural variations within the terrain (ESRI, 2009).

As described in section 4.5.3.2 the man made terrain including roads, embankments and buildings which were integrated in the DSM and their respective values were obtained from the fieldwork and previous data bases. The embankments were measures and accommodated within the DSM. For the roads generalization was

made in the form of primary, secondary, service roads and tracks. An approximate height of 0.5m, 0.3m, 0.2m and 0.1 m was assigned to different kinds of roads for example primary roads, secondary roads, service roads and tracks were incorporated within the DSM based on field observation.

### 5.2.2. Data Integration

While integration of the man-made and the natural terrain certain technical difficulties were faced. For example, the incorporation of the stream network shape file which in this case is the River Ubaye during interpolation was simplified by eliminating the morphologic features within the river bed. This was done to have an un-braided structure; otherwise it could not interpolate the actual value of the surface or river bed in this case. The building foot print layer has been used for the value addition for the physical elements while there were certain changes for example increasing the height of the embankment during the two events of 1957 and 2008; the changes have been incorporated and two DSM's were generated. The dyke and the embankment were included with respective heights and included in the final DSM. The following figure (Fig.5.8) for example illustrates one of the DSM's used for the 2008 event modeling.



*Figure 5. 8.3D representation of the final DSM used for 2008 Flood event modelling*

### 5.3. Hazard Assessment Through Generation Of Hazard Maps Using SOBEK1D2D

Flood scenarios were generated for hazard mapping using the 1D2D hydrodynamic models SOBEK. Some pre-processing and preparation of the data were required before going into the model directly. The preparation of data for flood modeling started with frequency estimation.

### 5.3.1. Frequency Estimation

The Gumbel curve (Fig.5.9) shows an estimation of frequency of occurrence of events of different return periods in terms of probability.

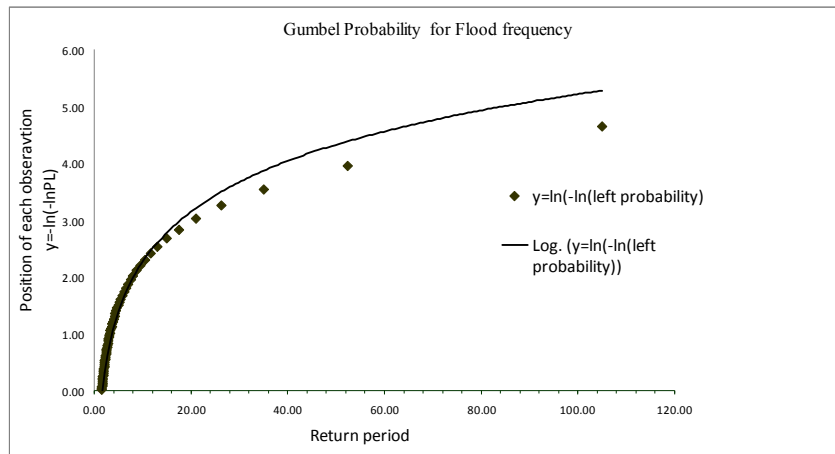


Figure 5. 9. Gumbel probability curve showing frequency of occurrence of events of different return periods

The model underestimates the two extreme events with very high discharge values as the curve does not fit well with this distribution of data. It has been tested using all the available 61 models of goodness of fit that the highest values of discharge for the two events are rejected statistically but they cannot be ignored since these are the two most important extreme events experienced in this area. This was due to the fact that these two values are extremely higher than the rest of the dataset.

**Table.5. 1.** Descriptive Statistics with and without extreme

Statistics	Value with extreme events	Value without extreme events	Percentile %	Value with extreme events	Value without extreme events
Sample size	104	102	Min	4.91	4.91
Range	445.09	77.15	5	15.375	15.34
Mean	41.98	36.63	10	18.95	18.81
Variance	2102.5	278.27	25	24.67	24.37
Std. Variation	45.48	16.68	50	34.1	33.75
Coef. Of Variation	1.09	0.45	75	47.15	46.17
Std. Error	4.49	1.25	90	62.9	56.19
Skewness	7.24	1.12	95	82.1	82.1
Excess kurtosis	62.34	1.29	Max	450	82.1



The table 5.1 illustrates the quality of data distribution using descriptive statistics with and without the extreme event values. Statistical models checked the goodness of fit of data and are appended to appendix 4. The model performance for the data base indicated that due to the irregularity in the two extreme values they were not taken as significant elements in the probability of occurrence in the Q-Q curves. Gumbel maximum and Pearson 6 models are chosen to illustrate the results here (Fig 5.10). The details of the statistical analysis using Gumbel and Pearson's statistical models for goodness of fit estimation can be obtained in appendix 5a and 5b.

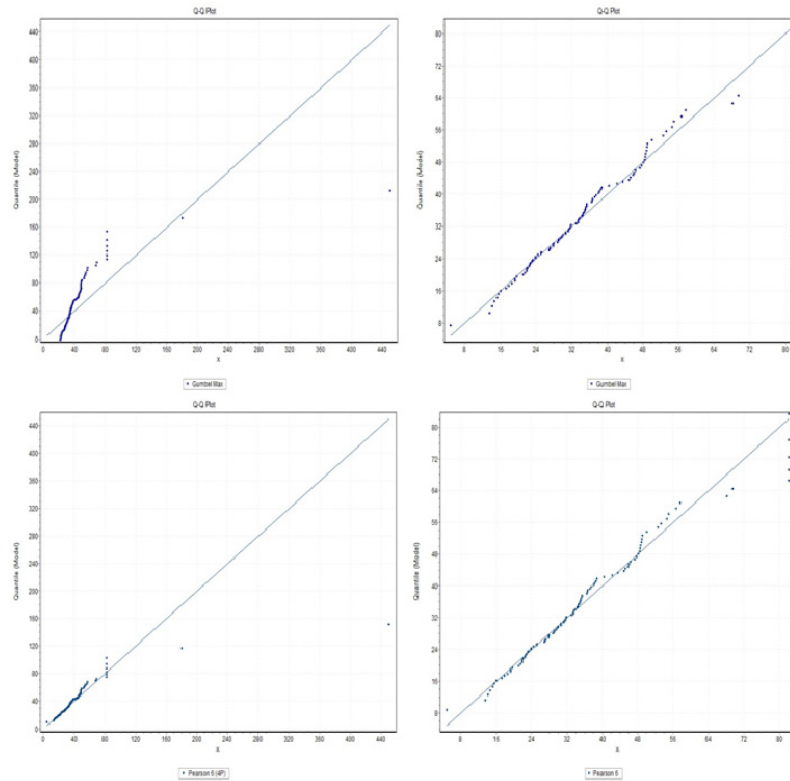


Figure 5. 10.Gumbel and Pearsons Q-Q Plot for analyzing the goodness of fit of the data with and without extreme events

The distribution clearly indicates for both Gumbel's and Pearson's that the extreme values were not well represented with these models and it affects the goodness of fit of the data and its distribution. The elements of descriptive statistics also show high level of variation in terms of skewness and variance.

Therefore a non-traditional way of identifying the actual return period of the extreme values was performed as shown in Fig.5.11.A trend line was plotted without taking into account the two extreme values. Further the line is extended to reach up

to the point where the extreme values are located within the graph and then the corresponding values for the return periods were identified.

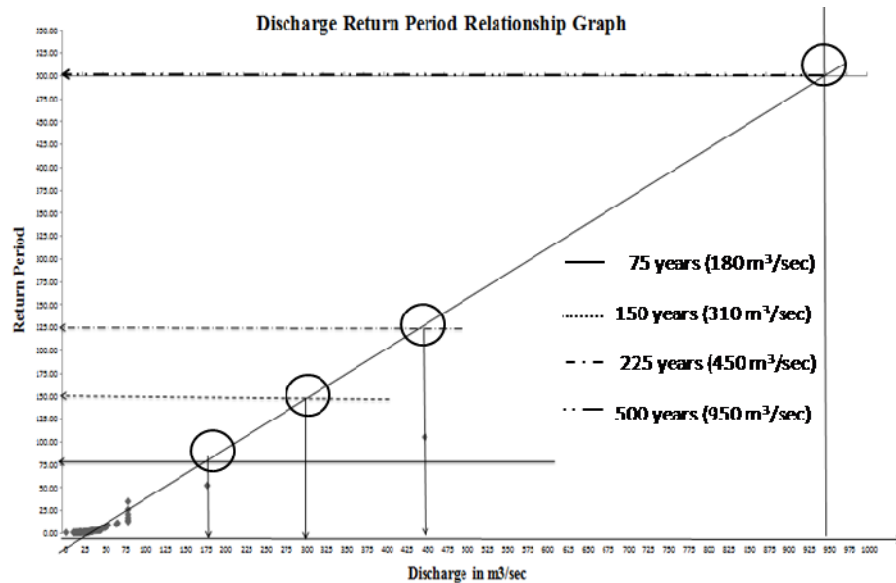


Figure 5. 11. Discharge vs. Return period graph to identify the actual return period for the extreme events

Based on the above data measurements of discharge for different return periods were identified. The result from the graph indicated that the value of return period for the 1957 event was a 225 year event while the near flood event of 2008 is a 75 years event. Similarly the discharge value for a 500 year event was also obtained from the graph.

### 5.3.2. Flood Hazard Scenarios

The flood hazard assessment was performed using the hydraulic model SOBEK 1D2D. The following discussion will bring into light the different phases of result generation and their respective importance for the study.

#### 5.3.2.1. Generation of Input Hydrographs:

The flood hazard analysis had been done using SOBEK 1D2D model. As described in the methodology section of this study (refer to section 4.6.1) the primary requirement for modeling the flood event was the appropriate hydrographs as an input for the upstream boundary for different return periods. Based on the available maximum daily discharge data it was not possible to generate hydrographs at a lower time scale for example on an hourly basis. However, the maximum values for different return periods were primarily identified using probability analysis.

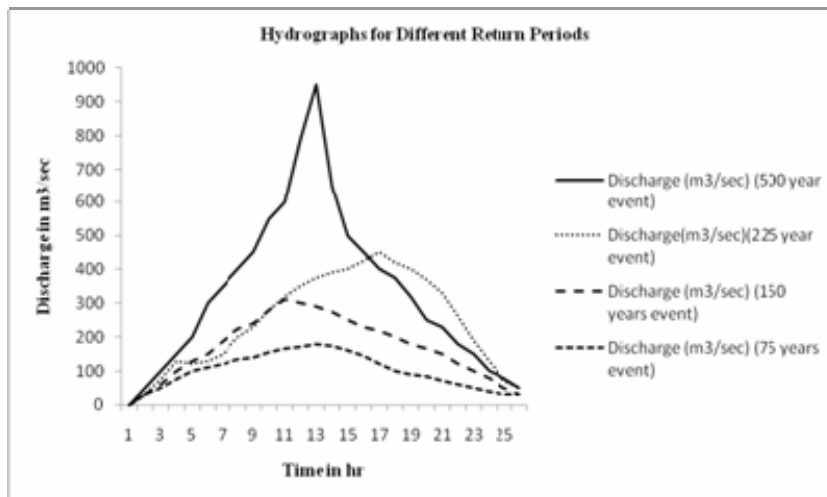


Figure 5.12. Hydrographs chosen as model input for 75, 100, 200 and 500 years return periods

The probability of a particular return period was chosen and the corresponding discharge data from the available discharge data were identified.

The hydrograph for the model input was generated based on the data of discharge few days preceding to the event chosen to some days after the event. The hydrographs were thus completely based on the estimation of the average data during the particular period of time. This was done in order to maintain parity between the actual data and the model input. The hydrographs were chosen model inputs for return periods of 75, 150, 225 and 500 years (Fig 5.12). The discharge values used to generate the hydrographs for different return periods have been attached to appendix 6.

### 5.3.2.2. Results of Flood Scenarios

The flood characteristics obtained from the model results were in the form of water depth, water velocity and impulse. All the maps were obtained for different chosen return periods. They were generated in the form of parameter maps. These maps were further analyzed for generation of hazard maps. The outputs of the model were in three forms; dynamic output, temporal output and spatio-temporal output.

The dynamic output included an animation file of incremental flood characteristics of propagation, depth and velocity at different time periods. The second type of output was in the form of time-series tables with water depth, velocity and discharge at predefined cross sections and other points within the reach. The examples for each of these tables can be seen in appendix 7. The third kind of output was the maps which were generated to define the spatial distribution of the depth, velocity and impulse of water at different time intervals. The parameter maps (maximum depth, maximum velocity and maximum impulse) generated for the different return periods

(100, 225 and 500) are shown in fig.5.13, 5.14 and 5.15. The parameter maps for the return period 75 was not shown as it can be noticed in the 100 year return period maps that the water does not overtop the banks therefore it is obvious that in 75 years return period also there was no overtopping. Therefore there was not much difference between the two set of maps.

As discussed in section 4.7 these were generated from the model output in the form of maximum depth, maximum velocity and maximum impulse.

**Table.5. 2.**Flood extent for different return periods

<b>Return period(in years)</b>	<b>Probability of occurrence</b>	<b>Water out of bank</b>	<b>Maximum Extent of water outside the channel( in m)</b>
75	0.013	No	00
100	0.01	No	00
225	0.004	Yes	450
500	0.002	Yes	470

The table 5.2 shows the extent of flood water out of the bank for the different return periods. The resultant flood characteristics obtained were flood depth, velocity and discharge values. The spatial extent of flood propagation depends upon the output of the simulation of different return periods. Based on the model results the event with a discharge of 450m<sup>3</sup>/sec (225 year event) there has been no overtopping from the banks. Hazard map for the area is then prepared using the parameter maps as base maps.

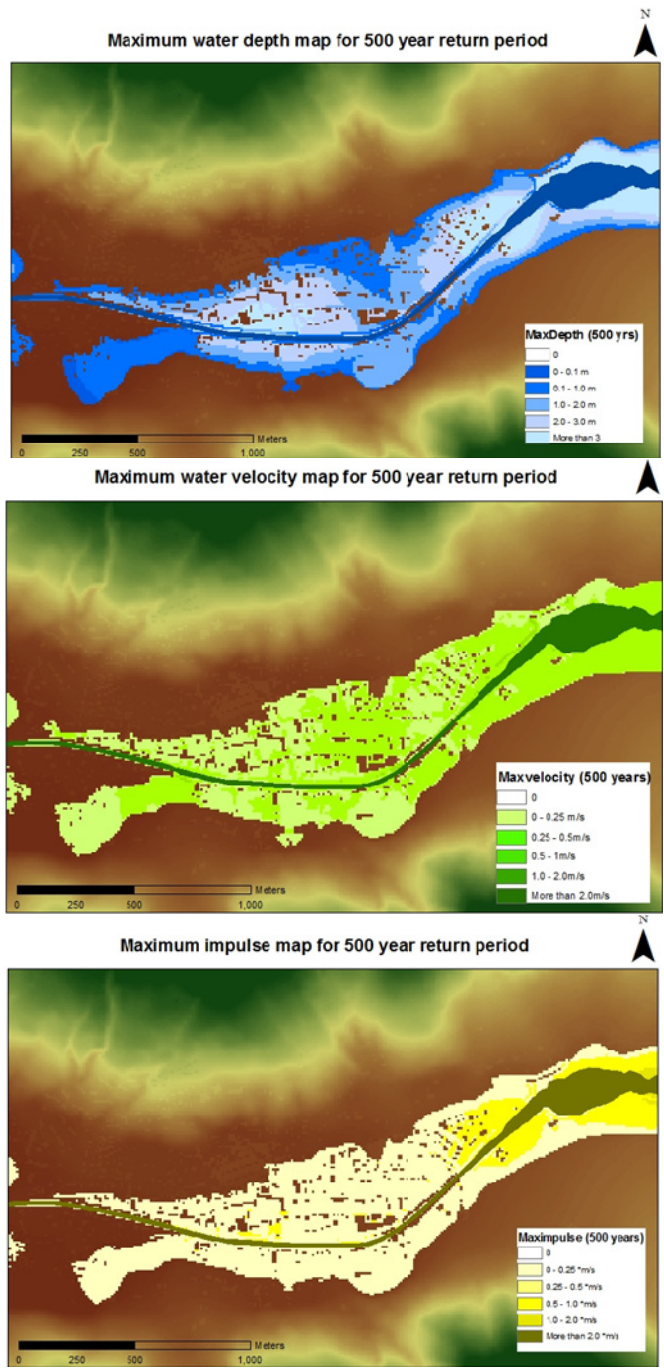


Figure 5. 13. Flood parameter maps for 500 year return period event

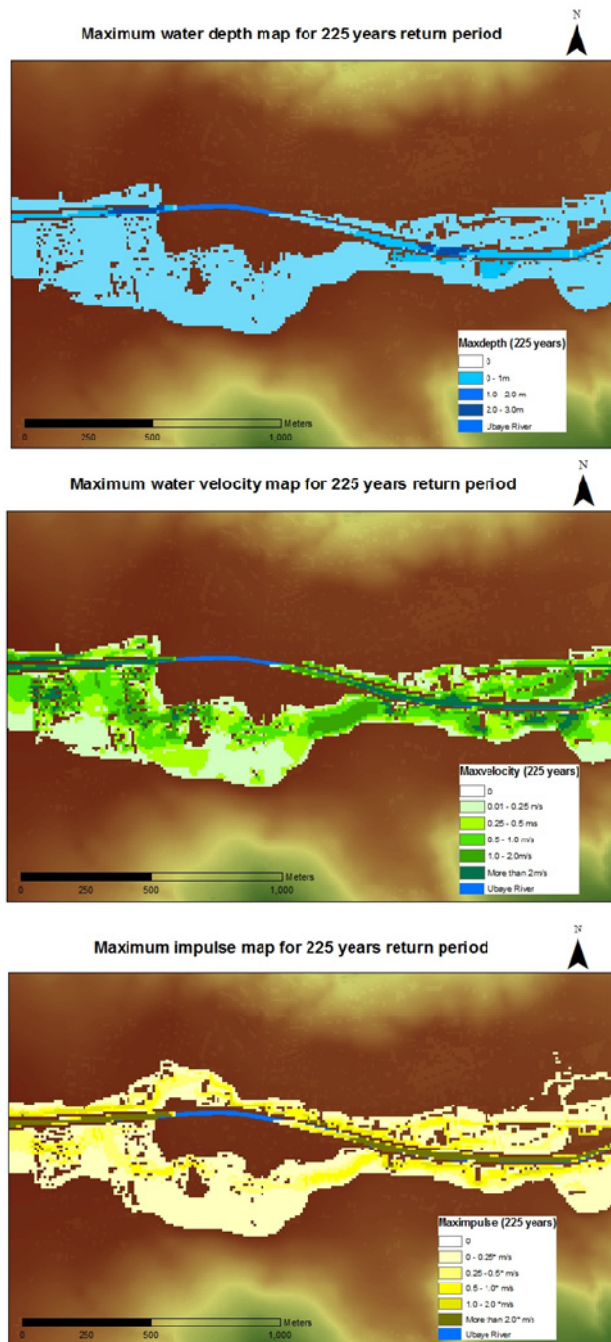


Figure 5. 14. Flood parameter maps for 225 year return period event

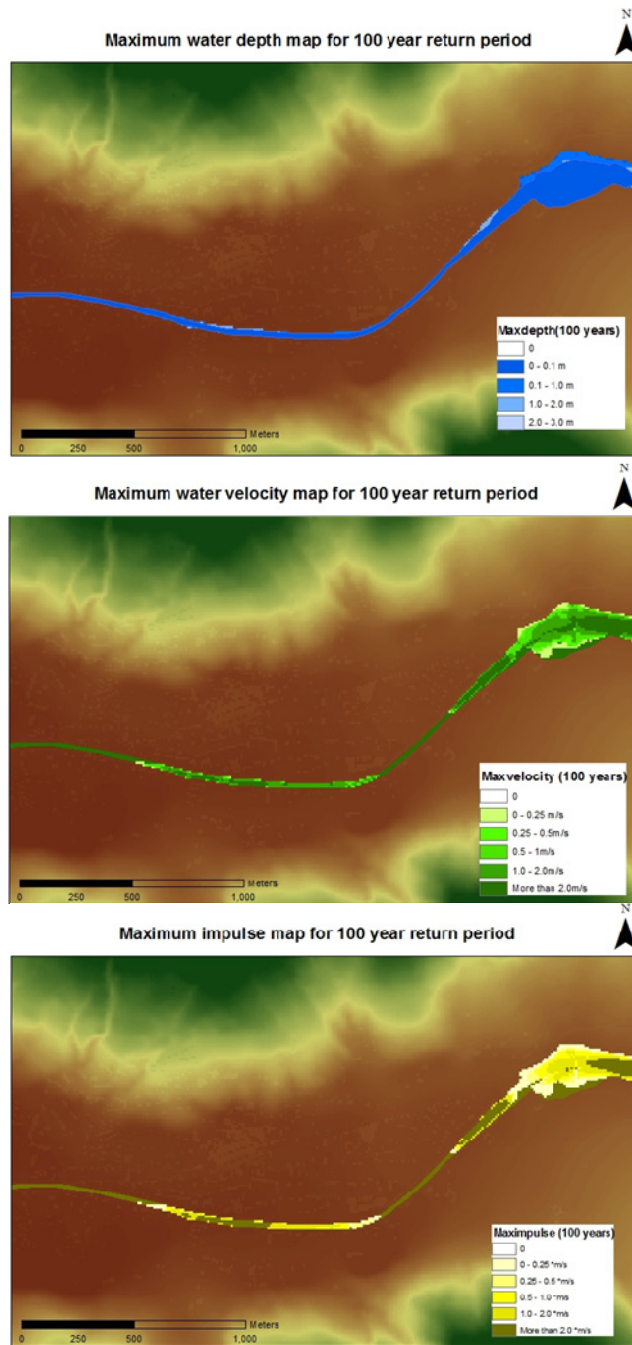


Figure 5. 15.Flood parameter maps for 100 year return period event

The figure 5.16 shows the flood hazard map of the area considering return periods 75,100, 225 and 500 years with their corresponding probability of occurrence. All the resultant scenarios were integrated to obtain the final flood hazard map to identify the zones for maximum hazard and those for minimum hazard.

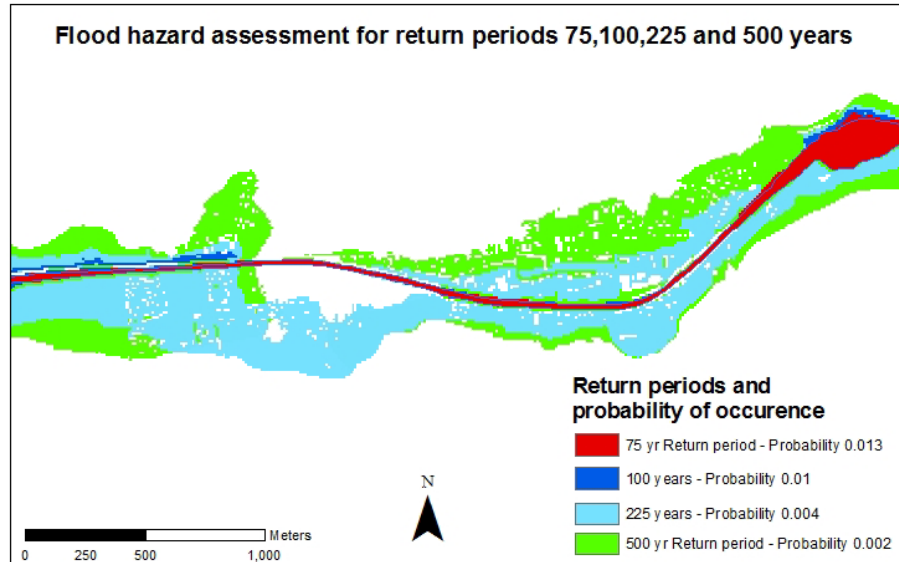


Figure 5. 16.Flood Hazard map for different return periods (75, 100, 225 and 500 years)

The red and the dark blue zones for 0.013 and 0.01 probability of occurrence indicates the area of highest hazard within the river channel but there was no overtopping of the bank. While the sky blue and the green zones shows the low probability of occurrence of 0.004 and 0.002 but there is overtopping from the bank causing higher risk to the nearby elements.

#### 5.4. Reconstruction of 1957 Flood event

For construction of historical event it is necessary to take into account three important factors:

- The factors that triggered the event
- The duration and frequency of the event
- The data available at the time of the flood event

The flood event of 1957 took place on the 14<sup>th</sup> of June till 17<sup>th</sup> of June. Various geomorphic phenomenon along with the climatic factors enhanced the damage caused by this flood. The climatic factors like the temperature, precipitation, snowmelt and wind were the triggering factors for the event. Various other factors for example accumulation of debris and particle size which varied from mud to



several cubic m worsened the effect. The local snow jams and the melting of the snow between 2000 and 2500 m followed by approximately 13 showers in a day (Tricart, 1958) naturally allowed the debris studded streams to flow down the valley at a very high speed where ever the slope was moderate to high. The uncertainty in the study of this catastrophic event dealt with the lack of availability of documents about the flood. The data was unavailable due to damage to the equipment installed and other circumstances causing interruption in reading. Therefore many elements that are needed to be known with high precision are speculated and create uncertainty in the study.

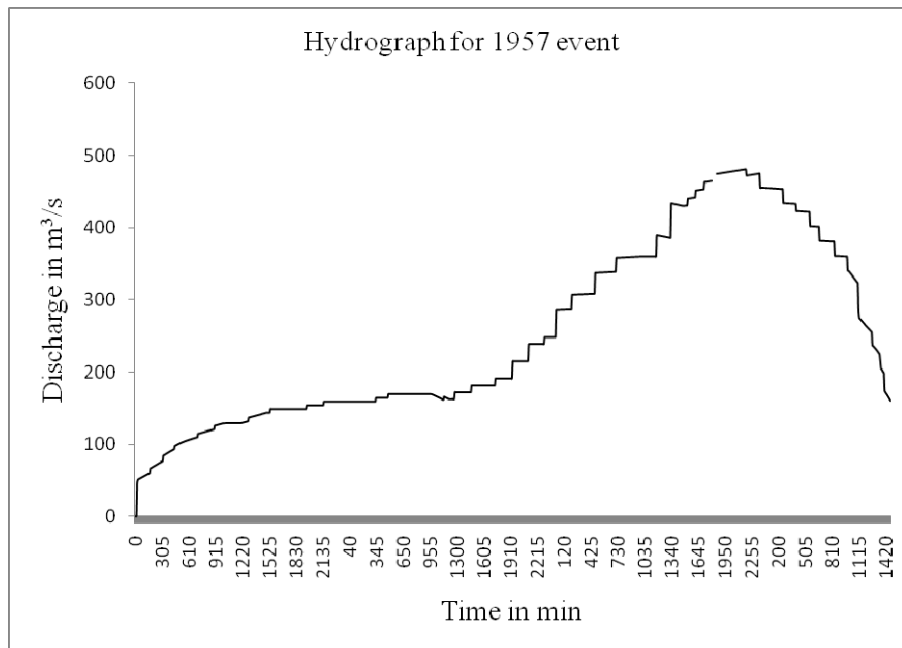


Figure 5. 17. Hydrograph for 1957 event

Based on the available measured data and the estimated data the flood event of 1957 was calculated to be a 225 year return period phenomenon. The hydrograph used for 1957 flood scenario is shown in Fig.5.17. The peak of the hydrograph reaches towards the end of the event with a steady increase in the discharge level throughout the period. The initial period of flattening of the curve may be attributed to the steady rise in the river water as a result of constant accumulation of water flow from several streams from upstream. The sharp increase in the peak discharge may be associated with the sudden snowmelt attributing to the warm wind from the south leading to increasing the water level several fold within very small period of time.

An essential factor that affected the intensity of the event was the amount of debris that was transported with the running water down the slope and blocked the river flow path. But there were no available data for quantity of debris accumulation

during the event. Therefore this factor was also not taken into account while modeling. Based on the assumptions that all other factors being constant only the estimated discharge data was used as an input to the model and the changed conditions were incorporated within the DSM (e.g., construction of the DSM based on lower dyke heights).

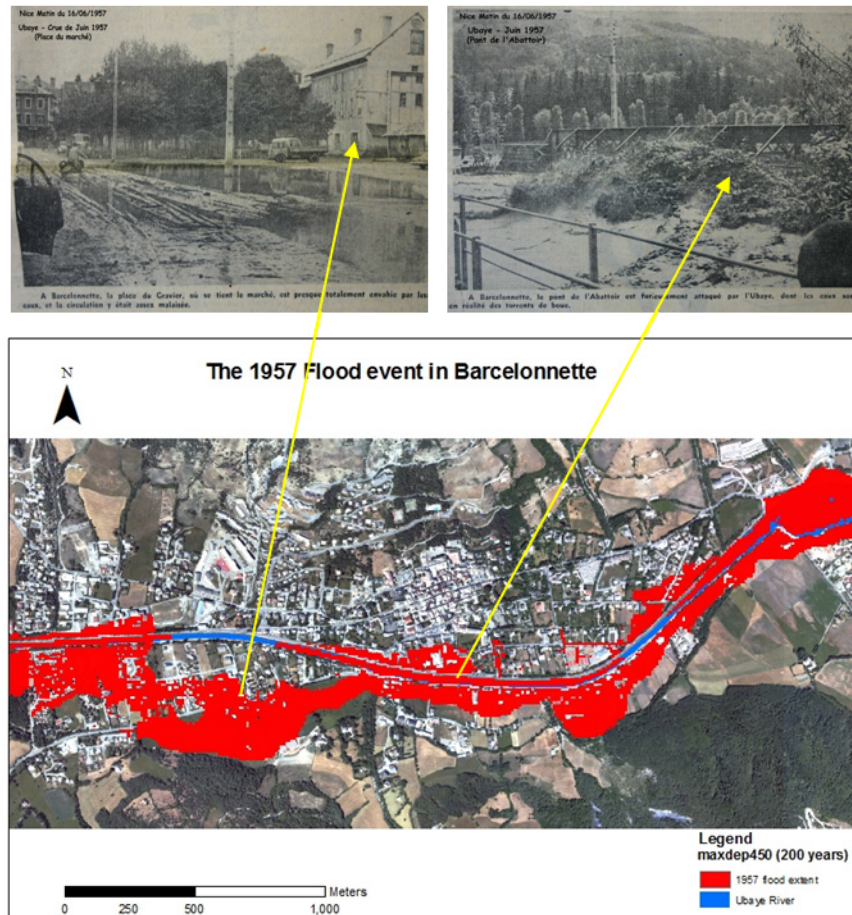


Figure 5. 18. The model result for 1957 flood event

The result from the model was obtained and validated based on the photographs available from RTM for the event and the extent of the flood was checked. There were no data for flood water depth or water heights during or after the event. So it was not possible to validate the results for this particular event with measurements based on observed and modeled data. The Fig.5.18 shows the flood extent of 1957 event and the two points of validation identified from the image which were affected during the flood. The model results showed that the maximum water height reached

during the event was 2.8m, with the maximum velocity of 6.48m/sec and an impulse of 8.92 m<sup>2</sup>/sec was reached with an extent of 450m.

#### 5.4.1.1. Reconstruction of 2008 Events:

The near flood scenario of May 26<sup>th</sup> to 30<sup>th</sup> in 2008 had alarmed the local authorities since it had been a while since 1957 that River Ubaye was so large and fast. It was threatened by the heavy rainfall and active snow melt in the upper slopes bringing in similar situation comparable to 1957. The water was still within the bank but the bridge “Pont de l'Abattoir” where the measuring station was located had its scale only few centimeters out of the river water. The condition of the bridge can be seen in figure 5.20 which was photographed during the event (source: RTM)

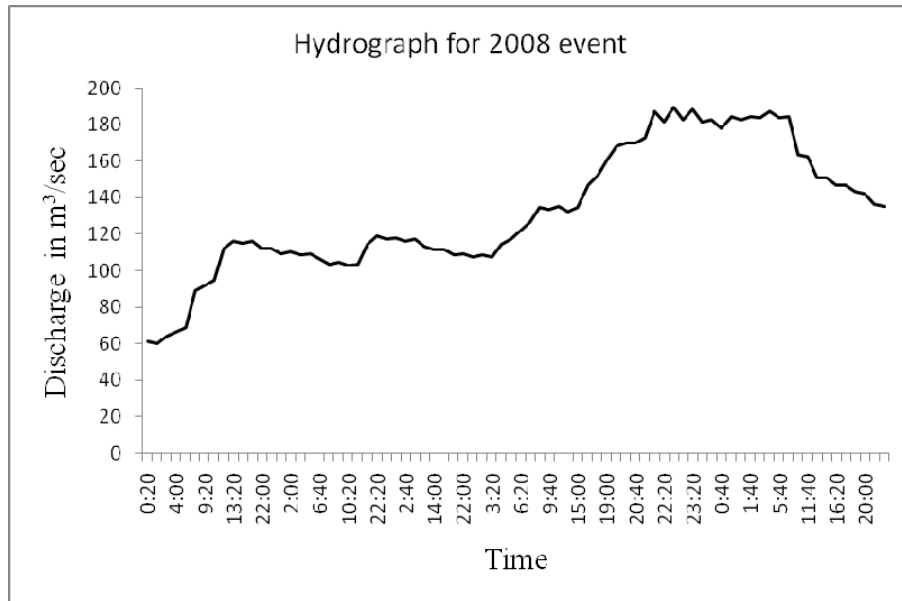


Figure 5. 19. Hydrograph for 2008 event

For the reconstruction of 2008 event the discharge data was generated from the available rating curve as explained in section 4.6.1 for the entire period of 4 days from 26<sup>th</sup> to 30<sup>th</sup> May 2008. The discharge values were in hourly basis and used as the input to the model. The hydrograph for the 2008 event is shown in fig 5.19.

The DSM (Fig.5.8) used for the generation of the flood scenario was adjusted to the present scenario by increasing the height of the dykes by 0.5m from that of the 1957 event. The output parameter maps generated by the model for the event indicated that this was a near flood event.



Figure 5. 20. Photograph showing the condition of Abattoir Bridge during the 2008 event (Source :Newspaper 30.05.08, Barcelonnette)

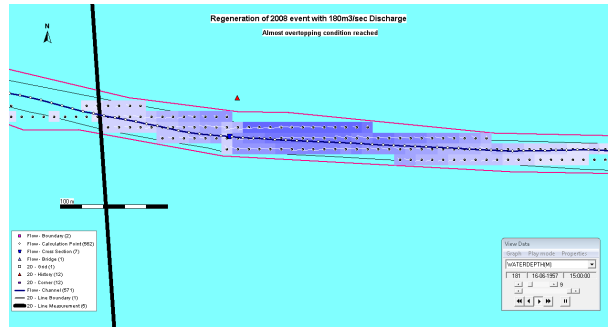


Figure 5. 21. SOBEK output for almost overtopping condition for 2008 event

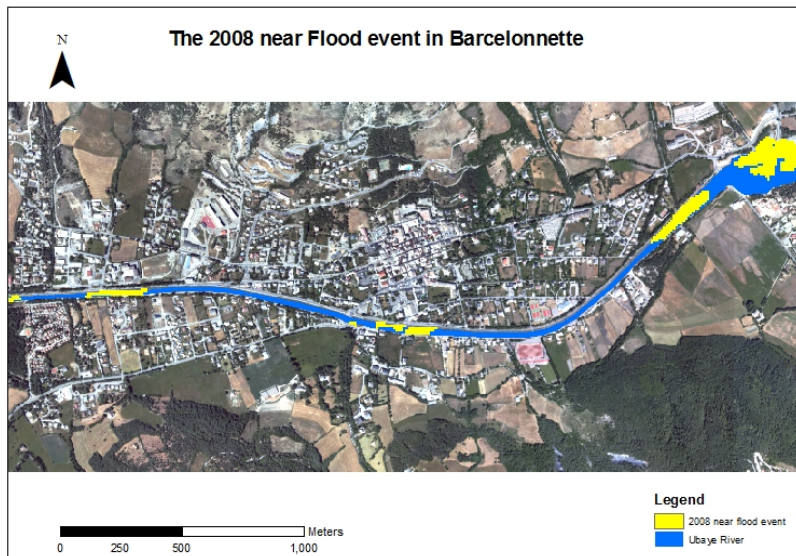


Figure 5. 22. Model result for 2008 near flood event

Figure 5.21 illustrates the model result for how the water reached up to a bank full condition in Ubaye which became the point of concern for the entire region. The

blue color indicates the river Ubaye and the yellow color in the map indicates the areas which almost overtopped. The highest depth of water during this event was obtained was 1.76 m. the maximum velocity of water was 2.9m/s and maximum impulse was 3.02m<sup>2</sup>/s. The differences at peak discharge between observed and modeled water height were around 0 to 0.4 m. The validation of the model results was performed by observed water height values which are further described in section 5.3.5.

#### 5.4.2. Generation of Friction surface

The calibration of the model was performed based on optimization of friction values within the channel. Manning's friction coefficients were assigned based on different land use types to generate a friction surface. The calibration of the model was based on the surface roughness parameter mainly within the channel. But the friction map was generated to produce a real world situation in the overland flow module.

**Table.5. 3.** Showing Mannings coefficient after (Chow, 1959) and (Tennakoon, 2004)

Landuse Classes	Mannings coefficient
Coniferous forests	0.10
Broadleaved forests	0.10
Natural grassland	0.35
Arable land	0.35
Pasture	0.035
Buildings	0.012
Urban fabric	0.012
Water course	0.001(varying)
Marshes and water bodies	0.035
Alluvial deposits	0.035

The table 5.3 illustrates the surface roughness values used for the model. The values were constant for the overland flow module but changes were made in the channel roughness parameter as indicated by the box for model calibration which have been discussed later in the next section 5.3.4.

Based on the above criteria friction map was generated and the Fig 5.23 illustrates them clearly how the values have been attributed to different land-use classes. Buildings were not included in the friction values as they were already included in the DSM. This became an issue later because with the inclusion of buildings within the DSM the flow of water through was hindered as the water surpassed the buildings and considered them to be solid blocks.

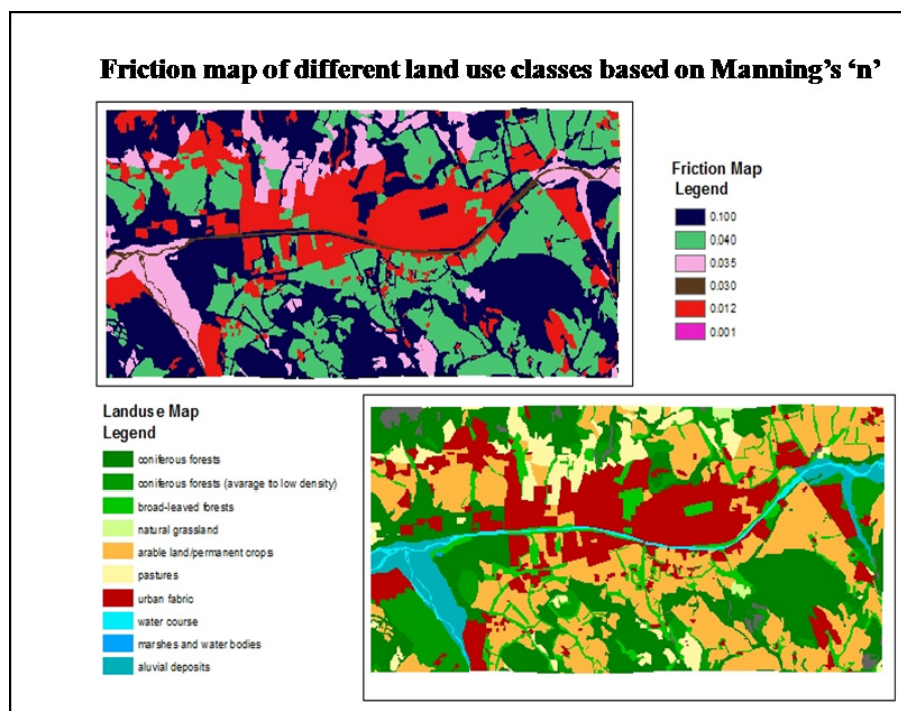
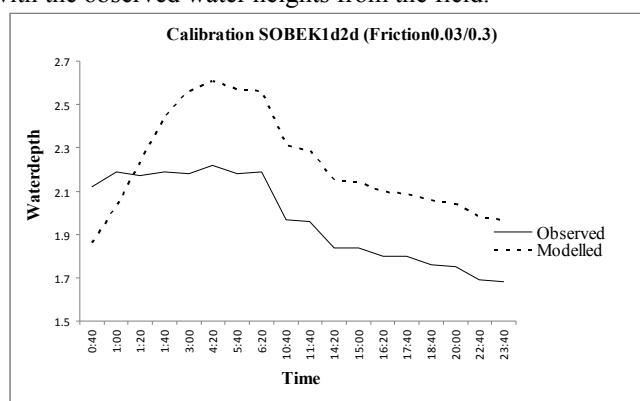


Figure 5. 23.Friction map Based on Land-use classes and corresponding Manning's coefficients

#### 5.4.3. Calibration and Sensitivity Analysis of the Model

Optimization of the model needs a clear agreement or disagreement between the observed and the computed values. Calibration tests (Muthukrishnan.S., 2006) the values of simulation outputs were compared to the observed outputs.

The calibration values were selected for one day i.e., the 30<sup>th</sup> of May 2008 and compared with the observed water heights from the field.



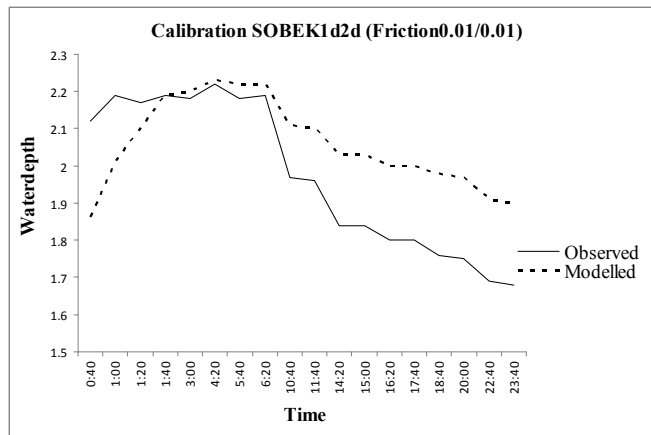
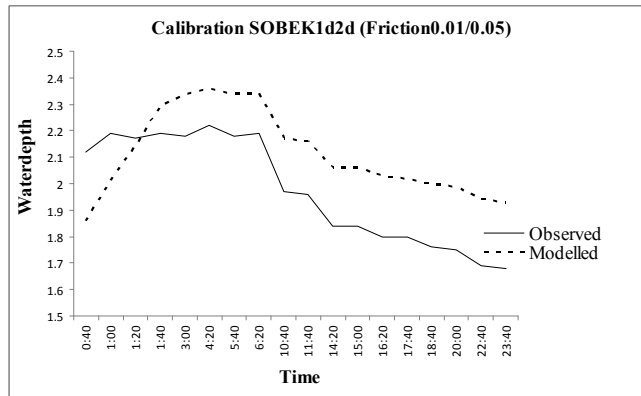
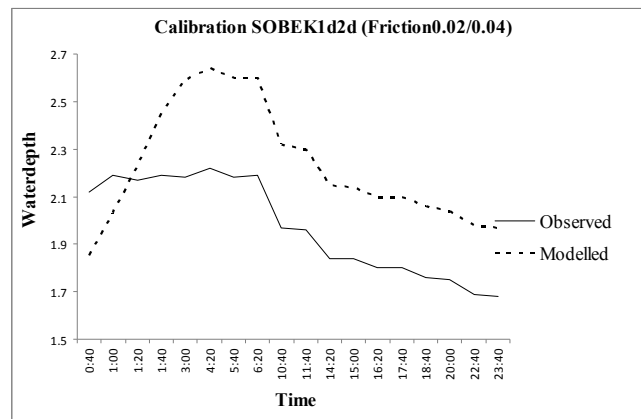


Figure 5. 24. Comparative graphs showing the observed and modelled water depths at Abattoir Bridge

The results for the different test runs based on different friction values to analyze the sensitivity of the model is shown by the comparative graphs of observed value and simulated values of water depths (Fig5.24). Calibration of the model was also done based on this sensitive element of friction value. The values correspond to the horizontal and the vertical friction values within the channel flow module respectively. The details of these terminologies and their characteristics can be seen in section 4.6.1.

The parametric approach of the model needs an analysis of the sensitivity of the model to different parameters. Model sensitivity to friction values were performed based on changing Manning's coefficient values of roughness within the channel. The surface roughness map for different land use types was generated for overland flow module (Fig5.23).

**Table.5. 4.** Comparison between observed and calibrated values for analyzing sensitivity of the model towards friction values.

Observed water depth (m)	Modeled water Depth 0.03/0.03	Diff-		Diff- at Abattior Bridge 0.2/0.4	Modeled water Depth 0.01/0.05	Diff- at Abattior Bridge 0.01/0.05	Modeled water Depth 0.01/0.01	Diff- at Abattior Bridge 0.01/0.01
		0.03/0.03 at Abattior bridge	Modeled water Depth 0.02/0.04					
2.44	1.86	-0.26	1.85	-0.27	1.86	-0.26	1.86	-0.26
2.6	2.03	-0.16	2.03	-0.16	2.01	-0.18	2.01	-0.18
2.74	2.23	0.06	2.23	0.06	2.14	-0.03	2.1	-0.07
2.87	2.44	0.25	2.45	0.26	2.29	0.1	2.19	0
2.87	2.56	0.38	2.59	0.41	2.34	0.16	2.2	0.02
2.9	2.61	0.39	2.64	0.42	2.36	0.14	2.23	0.01
2.87	2.57	0.39	2.6	0.42	2.34	0.16	2.22	0.04
2.88	2.56	0.37	2.6	0.41	2.34	0.15	2.22	0.03
2.71	2.31	0.34	2.32	0.35	2.17	0.2	2.11	0.14
2.7	2.29	0.33	2.3	0.34	2.16	0.2	2.1	0.14
2.6	2.15	0.31	2.15	0.31	2.06	0.22	2.03	0.19
2.6	2.14	0.3	2.14	0.3	2.06	0.22	2.03	0.19
2.57	2.1	0.3	2.1	0.3	2.03	0.23	2	0.2
2.57	2.09	0.29	2.1	0.3	2.02	0.22	2	0.2
2.53	2.06	0.3	2.06	0.3	2	0.24	1.98	0.22
2.52	2.04	0.29	2.04	0.29	1.99	0.24	1.97	0.22
2.47	1.98	0.29	1.98	0.29	1.94	0.25	1.91	0.22
2.41	1.97	0.29	1.97	0.29	1.93	0.25	1.9	0.22

The area of interest lies in the section of Ubaye River which is regular and channelized in shape due to the existence of the embankment. The reach length was 5501.85m with 7 cross sections and 4 bridges. The riparian vegetation was moderate to low in nature with predominant channel substrate of cobbles, pebbles and sand (Wilson and Atkinson, 2007),(Horritt and Bates, 2002). There were few large boulders within the channel but they were very rare. Based on these factors the friction values were determined and tested for the sensitivity analysis. The table (Table 5.4) summarizes the outcome of the analysis. It was interesting to notice that



the Manning's 'n' values with a vertical and horizontal friction of 0.01/0.01 entailed the most accurate results when compared to other test runs followed by 0.01/0.05. The average of the observed and simulated values of water depth ranges for different friction values from 0.24m , 0.26m, 0.13m and 0.08 m respectively. The model slightly over estimated as well as under estimated the values in the boundary regions but at the peak discharge areas the range of difference for the best simulation is 0 to 0.04 m. This may be due to the reason that the comparison is done only for one single point for Abattoir Bridge. More observation points within the reach could have allowed for flood routing leading to better calibration of the model. Based on various previous studies (Alkema, 2007) SOBEK1D2D model for flood hazard had predicted satisfactory result taking in to consideration the data availability and quality.

#### 5.4.4. Validation

The validation of the model simulation was done with such an event that the effect of the model can be assessed on extreme event. Therefore the event of 2008 was chosen since the observed water height data in an hourly basis for the event period was available and it was a near flood event .The validation data was obtained from the observed water heights from the same location of Abattoir Bridge and plotted together to see the difference as shown in Fig.5.25. The validation result showed an average difference between observed and modeled data to be 0.19m and the range of difference at the peaks to be 0 m -0.09 m.

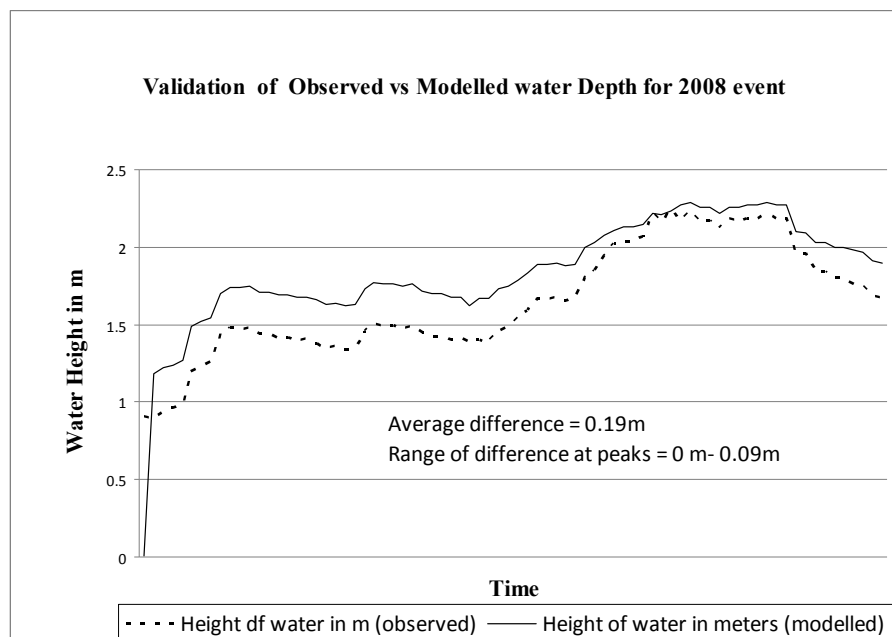


Figure 5. 25. Validation of the Model using 2008 event data

But at the peaks the model showed parity with the actual results. The possible reasons for over estimation of the model results may be explained by several possible sources of errors for instance the Q-h relationship, shape and nature of hydrographs, resampling of the DTM, volume of objects like trees ,crops etc and friction values (Alkema, 2007).

The next section of the research dealt with the assessment of risk which was derived from the hazard maps generated using model results and the identified vulnerable elements. The next chapter therefore will continue with the process and move one step forward to the total risk assessment of Barcelonnette town.

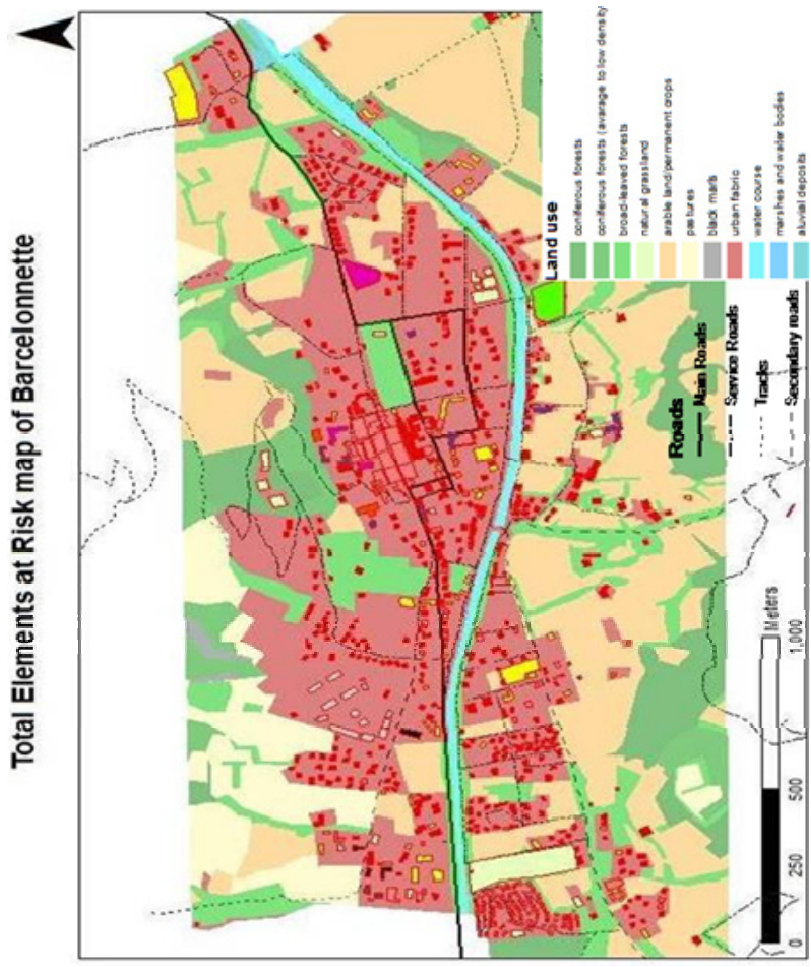
## **6. Risk assessment**

The central theme of this chapter is risk analysis. It looks into the various results derived from the methodologies of risk assessment described earlier in chapter 4. The different ways that risk had been assessed and expressed are based on qualitative and quantitative methods. The chapter first explains about identification and expression of vulnerability. Further it goes into the details of integration of the vulnerability aspects with the hazard to express risk.

### **6.1. Assessment of the Physical Elements At Risks**

The total numbers of physical elements at risks were identified based on the vulnerability curves as described in section 4.9. The actual elements at risk were obtained by overlaying the hazard maps for different return periods (225 and 500 are used as they are the ones where the water overflows the banks) with the total number of elements present in the area. All the elements (number of infrastructures) at local level which fall under a particular hazard zone based on their return periods 225 and 500 years were identified. However concentration was provided mainly to the return period of 225 as it was equivalent to the 1957 event. This was derived from the defined values exposed to the existing flood hazard in the area based on the flood hazard map in fig.5.12 and the foot print map of the different elements existing in the flood plain area shown in fig 6.1. Investigation was done on the number of affected elements i.e., the building types and functions. The other vulnerable elements investigated in the area were the affected essential facilities such as roads and the functions of the elements with special reference to emergency facilities like police station, hospital, school and fire station. This was essential in order to get an idea of services that will be required to provide to the local community in times of emergency that may happen in the area if an event of the intensity of 1957 occurs at present. The fig.6.2, fig 6.3 and fig.6.4 shows the identified elements at risk in terms of land use, urban infrastructures and roads and critical elements in Barcelonnette for the return period 225. In fig.6.2 the buildings were identified based on their functions. There were 323 elements which were effectively influenced by the flood event of 225 years. The critical elements have been indicated in the map to show if they will be affected or not should an event of similar magnitude occur. In 6.3 the land use classes that were affected is shown. The affected area shows that there was almost 0.19 km<sup>2</sup> of forest area, 0.15 km<sup>2</sup> of arable land, 0.3 km<sup>2</sup> of urban area were affected by the event. Based on the calculation of total affected road in fig 6.4 it was observed that in an event like 1957 at the present situation will affect about 4.5km of main roads, 0.5 km of service roads, 1.18 km of tracks and 0.67 km of service roads will be affected. These observations can be further used for indicating the level of accessibility during a flood event for evacuation purpose.

- Elements at Risk**
- Administrative
  - Administrative+commercia
  - Agricultural
  - Barracks
  - Bus Station
  - College
  - Commercial
  - Educational
  - Garden
  - Garage
  - Green house
  - Health
  - Industrial
  - Industrial\_artisan
  - Leisure
  - Medical Centre
  - Newspaper kiosk
  - Parking lot
  - Private Garden
  - Religious
  - Res+Indus
  - Residential
  - Residential+commercial
  - Service station
  - Storage
  - Terrain sport
  - Warehouse



**Figure 6. 1. Total elements at risk**

Elements at Risk map for buildings of Barcelonnette for 225 years event

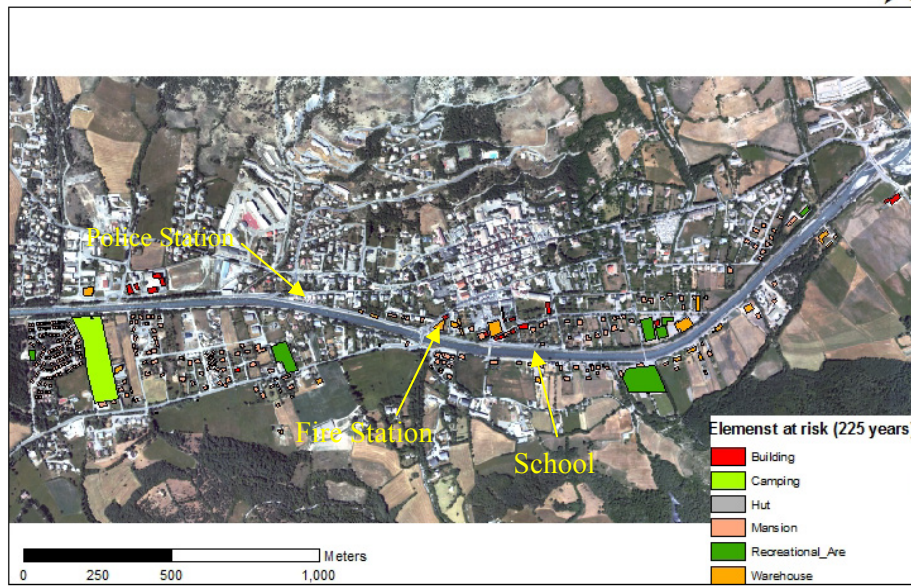


Figure 6. 2 Elements at risk for buildings in Barcelonnette town

Elements at Risk map for Landuse of Barcelonnette for 225 years event

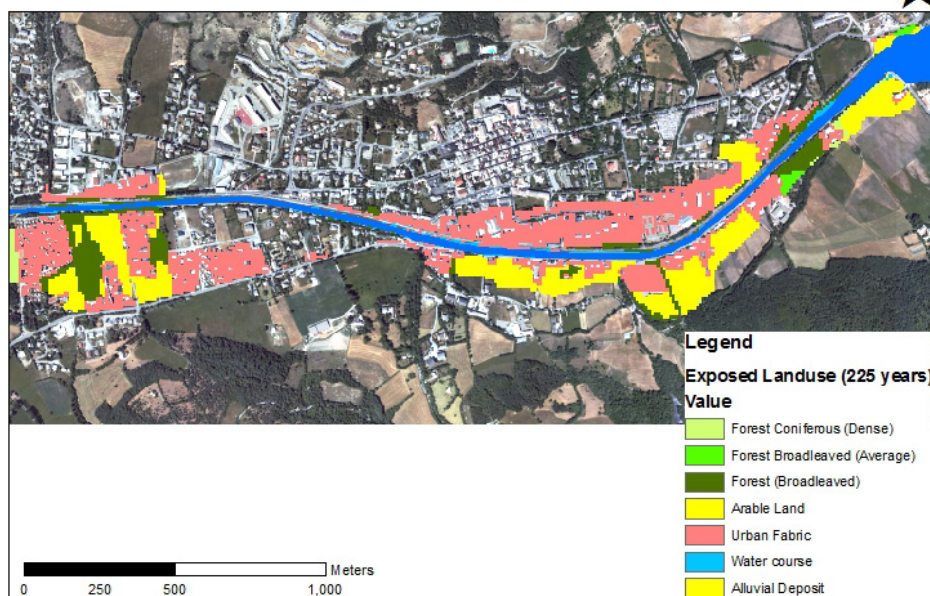


Figure 6. 3. Elements at risk for land use in Barcelonnette town

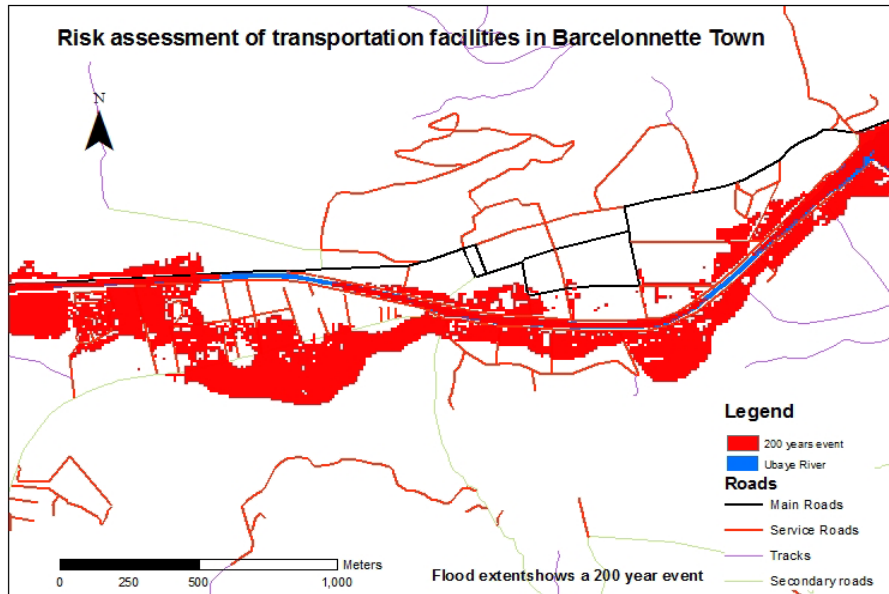


Figure 6. 4. Affected Transport elements in flood of 225 years

Not only in terms of safety but also this may have an economic impact on the real estate's near the flood plain if the dissemination of knowledge of the risk elements are made available to people. The delineation of the vulnerable elements was therefore an essential aspect of the study. Based on the analysis of the impact of flood events of different return periods it can be concluded that the area is prepared for a flood event of 100 years though it shows signs of concern but not prepared for an event larger than that.

## 6.2. Vulnerability Assessment

As discussed in section 2.6 and 4.9 the vulnerability curves from UK, Germany and France were used for the analysis. All these three vulnerability curves were based on the flood depth and its relative damage functions are shown in fig 6.5.

The vulnerability curve or damage function of UK was based on the vulnerable elements such agricultural land, houses, paddy fields, utensils, depreciable assets and inventory assets. The German damage function had simplified the classification based on land use types such as settlement, industry, traffic and green corridor. Similarly the French damage function indicated the damage value of the houses based on the depth of flood water.

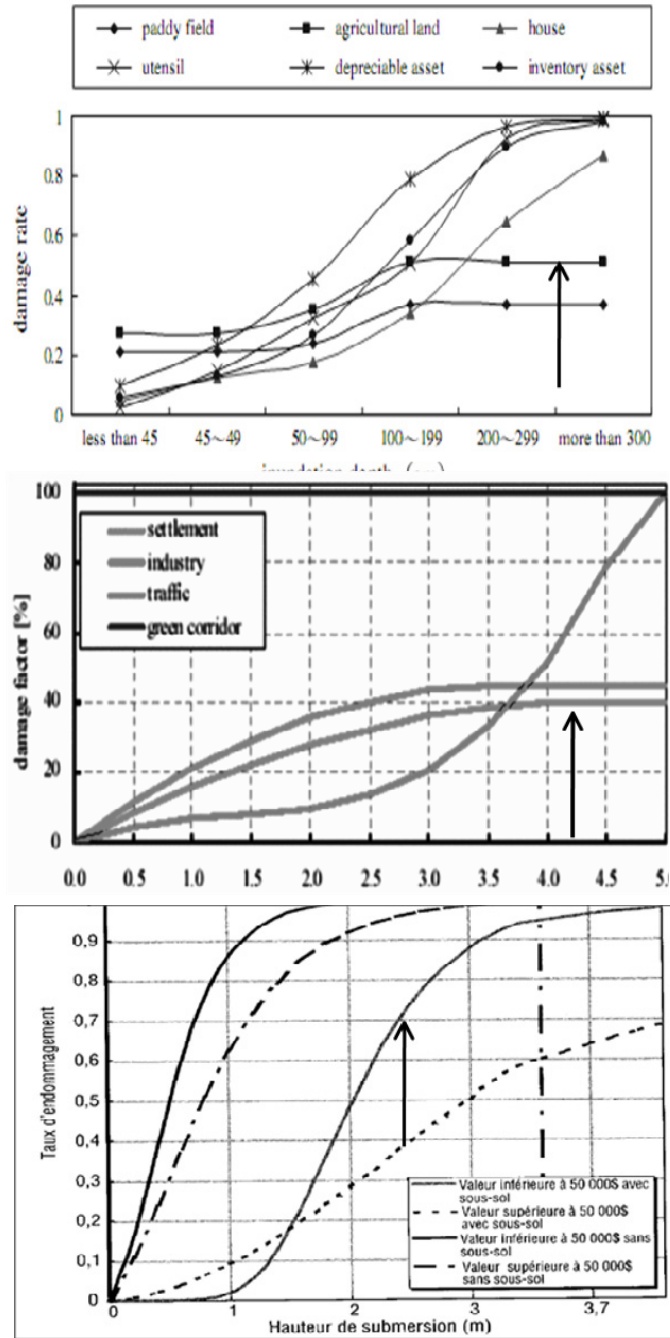


Figure 6. 5.Stage damage functions (1.UK, 2.Germany and 3.France) Arrows indicate the curves used.

The land use classes used for the present study were agriculture, urban area and forest area. The values for industrial and urban area were based on graph from Germany while for agriculture the values from UK function were adopted. The French damage function was mainly used for the estimation of cost of buildings with reference to the depth of flood water. Based on the above functions the vulnerability curve specific for the study was plotted as shown in Fig.6.6.

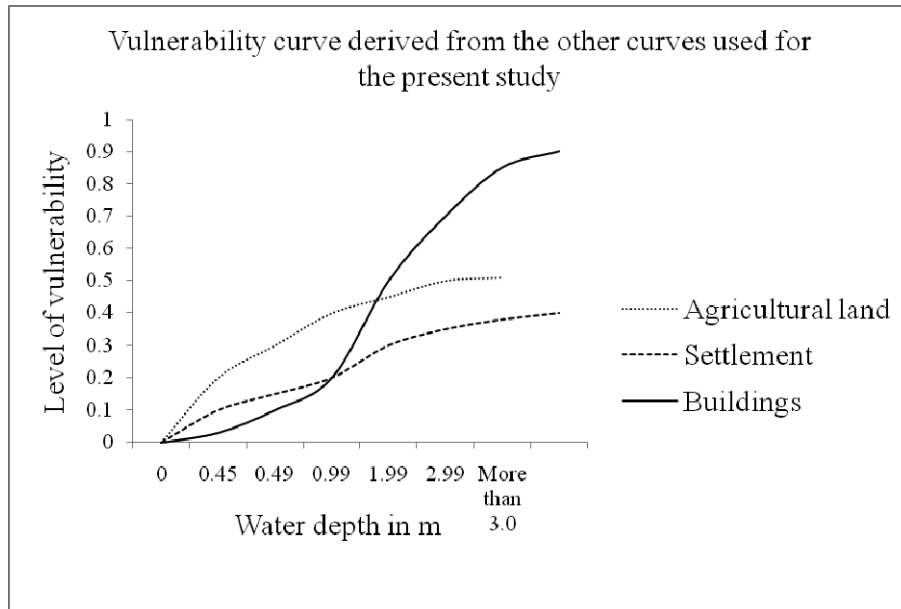


Figure 6. 6.Vulnerability curve for the present study

### 6.3. Vulnerability maps

Based on the damage functions damage maps for individual land use types were identified. The vulnerability for the land use classes of highest weights i.e., the urban fabric, agriculture and forests were identified. Fig.6.3 illustrates the vulnerability of the identified land use units in terms of percentage damage for the 225 years return period. This particular return period is used for the damage assessment because it was same to the 1957 flood event showing the effect on the present land use. The intermediate damage percentage maps were generated and were appended to appendix 8.



Vulnerability map for different Landuse classes based on vulnerability curve<sup>N</sup>

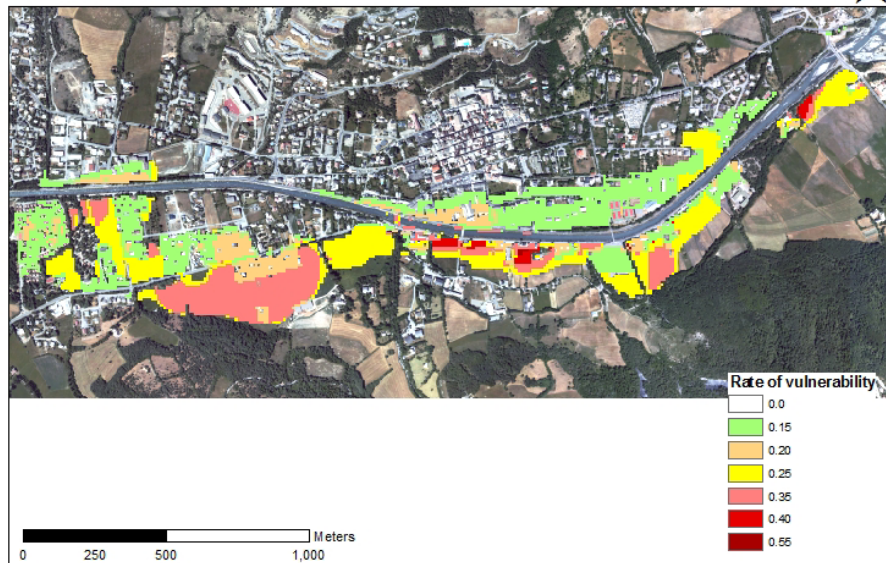


Figure 6. 7. Vulnerability map of Land use classes (Agriculture, urban area/settlements and buildings on Depth Damage functions)

Vulnerability map for different Buildings based on vulnerability curve<sup>N</sup>

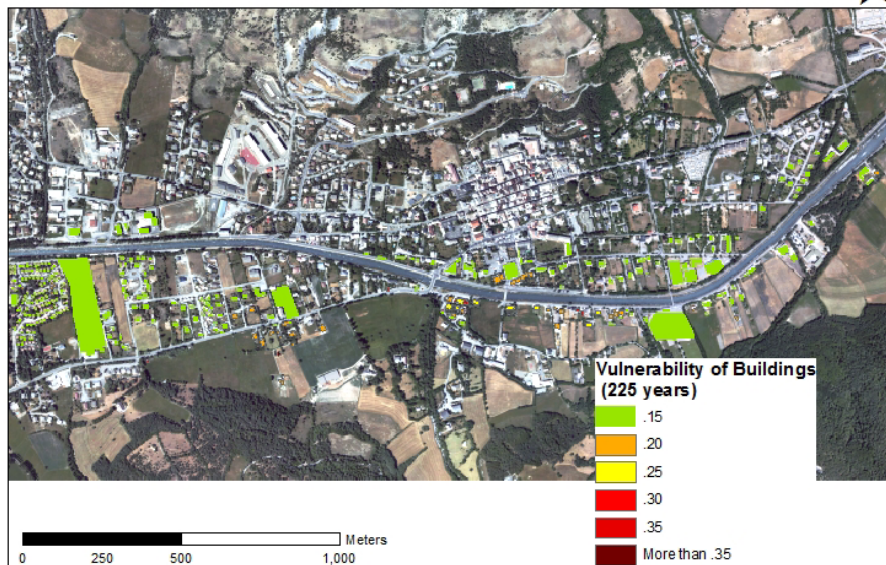


Figure 6. 8. Vulnerability Map for buildings and infrastructures

The vulnerability map for the different land uses derived from the vulnerability curve are shown in fig 6.7. The result for the vulnerability of the physical elements at risk has been displayed in fig.6.8. The intensity of damage or vulnerability of land use and buildings are indicated through the color scheme in both the maps. This was the base map that had been further used for the risk assessment of the different elements.

#### 6.4. Risk Assessment

The risk assessment was done based on the model simulation results and the identified vulnerable elements at risk. Two factors were considered while assessment i.e., the magnitude and the probability of occurrence of risk. However, not all the values for the quantification of risk for different land use types were available. Therefore another approach of qualitative analysis of risk was applied as described in section 4.10.

##### 6.4.1. Qualitative Risk Assessment

Based on flood depth a map and the vulnerability map for different land use classes the qualitative assessment of risk was performed. The various land use classes were weighted according to their level of importance in the economy. Table illustrates the relative weights assigned to various classes of land use.

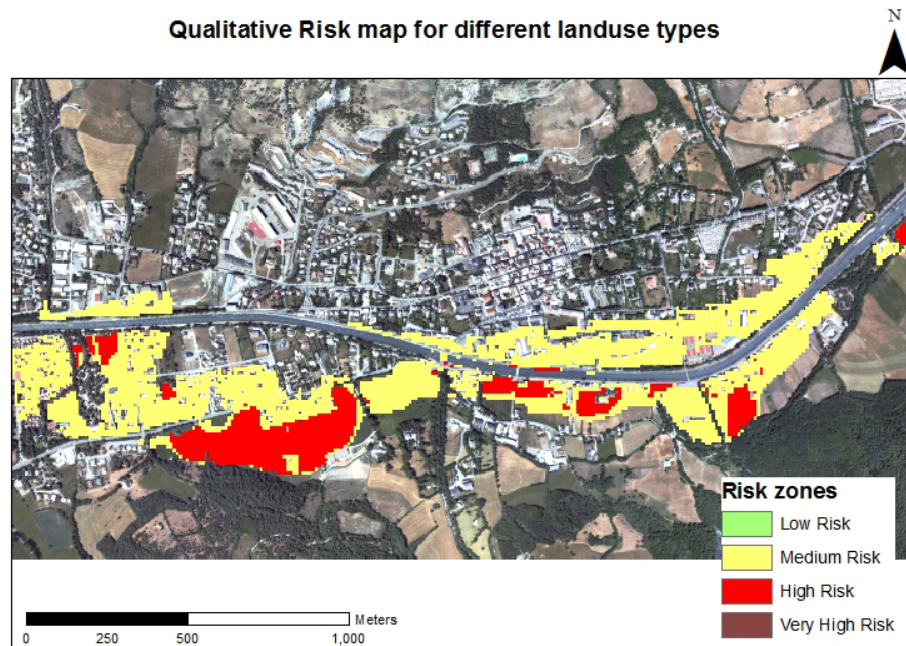
**Table 6. 1. Showing the weight assigned for different land use classes**

S.no	Land use types	Assigned relative weight
1	Forest	20
2	Arable Land	50
3	Urban fabric	100

Based on the weights assigned for a particular land use type and higher level of vulnerability the zones for risk maps were identified. The area with higher vulnerability and higher hazard leads to higher risk and *vice versa* as illustrated in table 6.2. Based on the above criterion the risk map (fig.6.9) was prepared which illustrates the qualitative assessment of the different land use types based on the exposure to a 225 year flood hazard with respective rate of vulnerability as explained in section 4.10.

**Table 6. 2.**Risk zonation based on hazard and vulnerability criteria

Type of assessment	Criteria assessment	of	Classification	Risk zones
Hazard	Water depth	of	0.0-0.5	Low
			0.5-1.5	Medium
			1.5 – 2.0	High
			Above 2 m	Very high
Vulnerability	Level vulnerability	of	0.0-0.1	Low
			0.1-0.3	Medium
			0.3-0.5	High
			0.5 and above	Very High



*Figure 6. 9. Qualitative risk assessment of Land use types*

#### 6.4.2. Quantitative Risk Assessment

Based on the methodology described in section 4.10 the identified exposed elements from the vulnerability maps (fig.6.8) were assigned with their respective average values in Euros to estimate the actual value of damaged assets. Table 6.4 and 6.5 shows the event damages that can be caused by the events of magnitude of return period 225 and 500 years.

**Table 6. 3.** Economic damage assessment of the Buildings based on damage functions classified on the basis of types (value based on interview with local real estate agents)

<b>Type of Buildings</b>	<b>Area Affected in sq mt for 500 year flood (approx)</b>	<b>Area Affected in sq mt for 225 year flood (approx)</b>	<b>Total damage (225 years) based on depth damage curve in million euros</b>	<b>Total damage (500years) based on depth damage curve in million euros</b>
Buildings/Flats	5854.95	5465.37	2.73	2.92
Mansions	33658.49	25248.5	2.4	15.34
Ware houses	10062.21	18147.11	2.48	5.57
Huts	202.03	150.34	0.05	.03
<b>Total damage</b>			<b>7.66</b>	<b>23.86</b>

**Table 6. 4.** Economic damage assessment of the Buildings in case of 100% destruction based on types ( value based on interview with local real estate agents)

<b>Type of Buildings</b>	<b>Area Affected in sq mt for 225 year flood (approx)</b>	<b>Area Affected in sq mt for 500 year flood (approx)</b>	<b>Value per sq mt in euros (estimated)</b>	<b>Total damage (500 years) in case of 100% destruction in million Euros</b>	<b>Total damage (225years) in case of 100% destruction in million Euros</b>
Buildings /Flats	5854.95	5465.37	3000	17.56	16.40
Mansions	33658.49	25248.5	3500	117.80	88.37

Ware houses	10062.21	18147.11	2000	20.12	36.29
Huts	202.03	150.34	1500	0.30	0.23
<b>Total Economic damage</b>				<b>155.80</b>	<b>141.29</b>

It was clearly visible in table 6.5 that the economic costs in case of complete destruction of buildings were much higher than the actual damage caused by such an event as shown in table 6.3. These estimations however give an idea of the probable maximum losses that is believed to be possible by a particular return period. This is further described by the risk curve which evaluates the annual average risk for the different return periods.

The sector wise economic values were based on the economic statistics the DDA has identified for as 2002 base year and had been inflated to 2.8% according to consumer item inflation rate from 2002 to 2009.

### 6.5. Generation of risk curve

The risk when represented in the form of a curve delivers the information of probability of maximum loss for a given return period. In fig.6.9.it can was seen that with higher probability of occurrence of an event the level of damage is lower than that of the rare events which cause much higher destruction

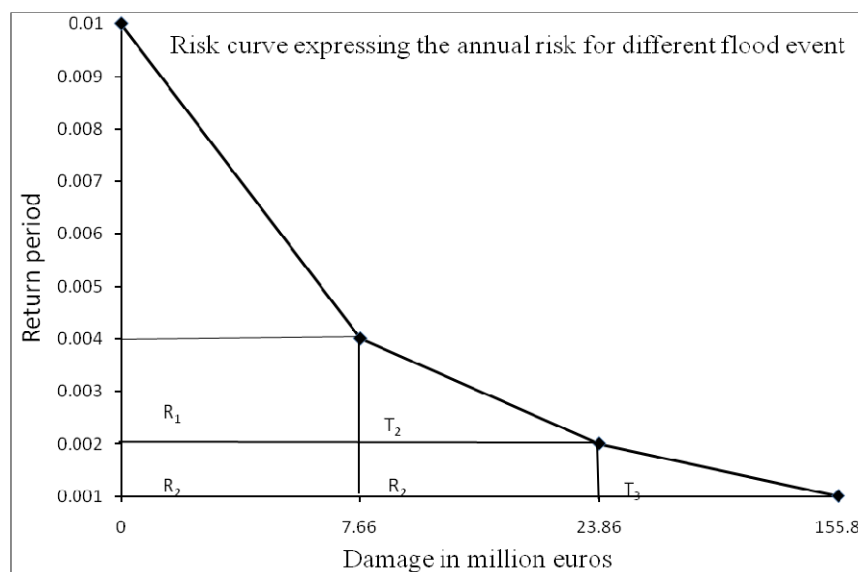


Figure 6. 10. Risk curve for economic losses for buildings for different return periods

. The area within the risk curve delineates the estimation of average annual risk for the area for different return period in monetary sum shown in the graph as  $T_1$ ,  $R_1$ ,  $R_2$  for 225 years  $T_2$ ,  $R_2$  for 500 years and  $T_3$  for the assumed event of the millennium. The annual risk for buildings is represented by the area within the risk curve he calculated values based on risk curve are shown in the table 6.5:

**Table 6. 5.**Average annual riskfor buildings of Barcelonnette

<b>Return period</b>	<b>Event damage</b>	<b>Area under the risk curve</b>	
225	7.66	$T_1$	0.023
		$R_1$	0.015
		$R_2$	0.015
500	23.86	$T_2$	0.016
		$R_3$	0.032
1000	155.80	$T_3$	0.131
Total Area			<b>0.233</b>

So the total average annual risk is  $0.233 \times 10^6$  Euro. This is the annual equivalent that the municipality should set aside to “insure” itself against flood events up to a return period of 1000 years. This calculation is useful when the municipality wants to make a cost-benefit analysis of possible mitigation measures. For instance, in the current situation a flood with a return period of 100 years (annual probability = 0.01) causes zero euro damage. If a mitigation measure can increase this safety level to once in 200 years, and the rest remains the same, then the area under the risk curve is reduced by  $0.015 \times 10^6$  Euro per year. In other words, the mitigation measure has a benefit in terms of avoided loss of 15000 Euros per year.

The calculation for the average annual risk is very sensitive to the effective preventive measures. Therefore the value for average annual risk investment will change if proper protection measures against flood are taken resulting in minimizing the amount of economic damage. This is a very important decision making tool for the authorities managing the funds for safety measures.

#### **6.6. Investigation Of The Effect Of Flood Plain Development On Flood Risk**

The flood plain development study was based on the changing nature of flood protection activities in the area and its direct impact on the degree of risk as discussed earlier in section 4.4.4. Several changes have occurred in the procedure of delineation of the risk zones in the last 25 years. Therefore it was investigated how far these changes correspond to the results obtained from the present study. The economic aspect of risk assessment and the value evaluation at present rates focused on the damage potential and estimation of expected damages which was very important for investment and policy making for the local authorities.

### **6.6.1. Changing Prevention Plans and Flood Risk over Time**

The methodology for delineation of risk zones used by the PER (Plan d'Exposition aux Risques) during 1985-1995 and PPR (since 1995) changed over time thus producing two different sets of prevention plans based on them. The criteria for delineation of different zones for PER and PPR were different which were tabulated and appended in appendix 9. The risk maps produced by RTM are also different. Therefore two sets of maps were generated to compare the results from the present study with these maps. This was performed in order to see which of these plans corresponds to a greater extent to the present research. The Fig.6.13 compares the risk zonation delineated by PER during 1985-95. The risk map was generated by RTM depending upon multi-hazard criteria (here zones based on inundations were only included). In the following Fig.6.8 the PPR delineated risk zones (1995 onwards) were compared with the present risk map. The prevention plans were based on the criteria associated with these maps and the zones for developmental activities are also affected by these regulations. It can be observed that the resultant map from the study based on the 225 year return period event corresponded with the limits of the zones delineated by the risk map by RTM in Fig 6.13.

Both the maps indicated that the zones are quite well designated and the regulations for the buildings and new infrastructures are well organized in most parts. However, in some areas especially in the Pont du Plan area of Barcelonnette the low risk zone in PER and designated blue medium risk zone in PPR coincides with the high risk zone delineated by the result from the present study. The result from the study clearly identified the regions from the both the maps that does not correspond to the prevention zones. They had either been associated with high risk zones or included in low risk zones. It is however essential to note that this zonation was based on extreme events such as 200 years and all the development activities are affected by the strict zonation based on these maps. Therefore on one hand very strict zonation may reduce the level of development that the area can achieve in the near future but if there is a lag in the protection zones then it can be disastrous for the exposed elements at risk.

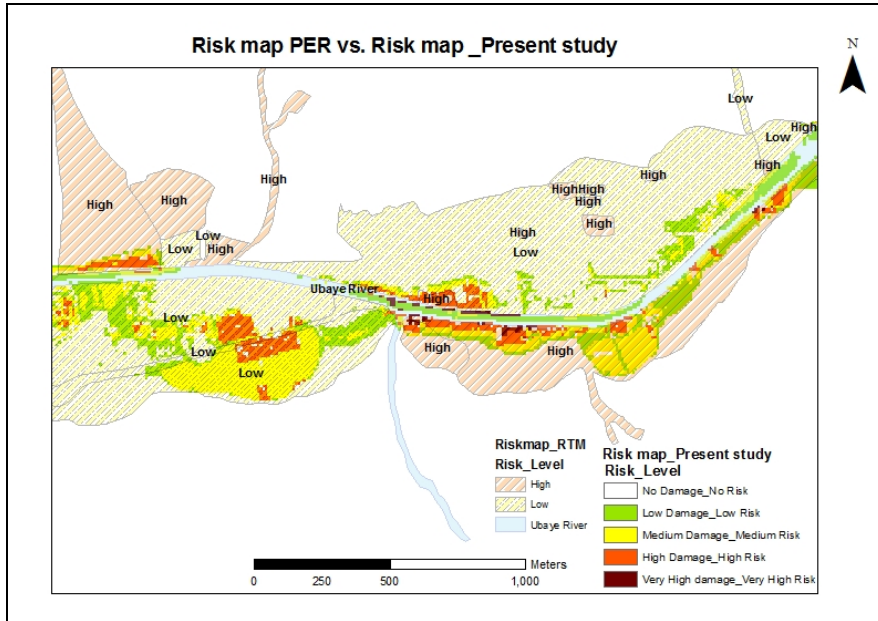


Figure 6. 11. Comparison between PER (1985-95) map and Risk map zones

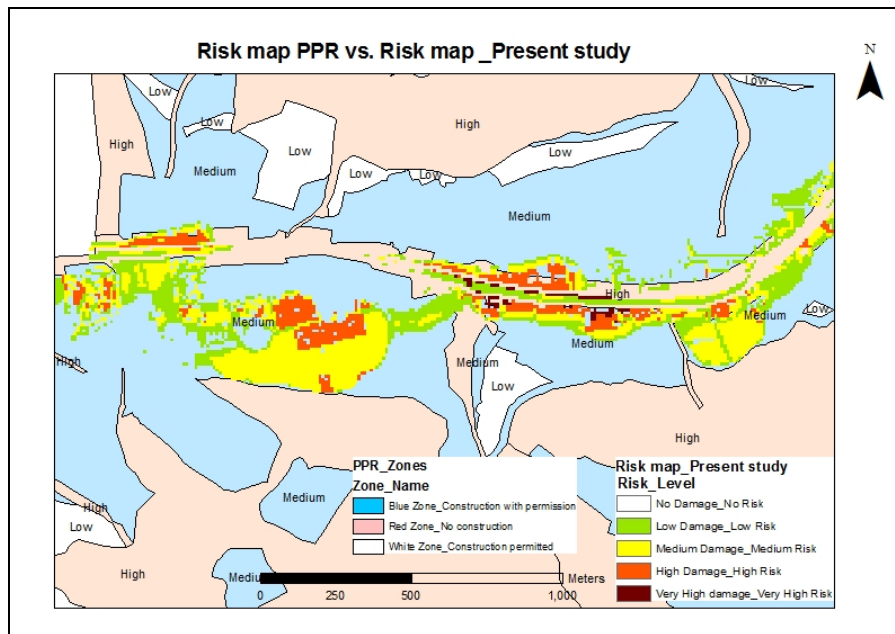


Figure 6. 12. Comparison between PPR (1995 onwards) zones and Risk map zones



## 7. Conclusion And Recommendation

The town of Barcelonnette is located in an area highly prone to multiple natural hazards such as landslide, debris flow, mudflow and floods. In this study methodologies were used to assess the flood hazard, vulnerability and risk for the first time in the study area. This was performed to strengthen the overall approach of understanding the flood risk assessment in the area. On the context of historical information of flood risk management the following insights were gained which are worth mentioning.

- Considering the fact that the event of 1957 happened a long time ago the people had mostly forgotten about it leading to unawareness of the risk which still exists in the area.
- The protection works sometimes creates the illusion of “Zero Risk” to people fostered by non occurrence of major floods for a long period of time. Therefore the concern over the near flood situation in 2008 was alarming for the authorities.

### 7.1. Specific Conclusions

Flood hazard and risk assessment study is a methodological approach which characterizes the regions damage potential. It is area specific and user specific in nature and needs better understanding of the flood characteristics and behavior for proper implementation of mitigation measures.

#### 7.1.1. Data Preparation

- It can be concluded that even with the existence of extreme set of data as seen in the discharge data it was possible to analyze the probability of flood frequency through non-traditional way.

#### 7.1.2. DSM Generation

- The grid cell resolution of 10m was selected for the study which served the purpose of representation of the surface for flood modeling in the area
- Incorporation of buildings in DSM caused problems in simulation result in terms of flow of water.
- The significant elements for the construction of DSM were based the area of study and the type of available data.

#### 7.1.3. Flood Modeling

- Two different types of hydrographs were generated for the study based on estimated values and measured values. The shape and changes in peak discharge of the hydrographs had substantial effect on the simulation result.

- The simulation results from the flood model revealed the flood characteristics of depth, velocity and impulse for the area for different return periods. The spatial extent of flood was obtained from the parameter maps.
- In regeneration of past events data constraint was the major issue of concern. But with a well calibrated model based on observed data for the 2008 event the regeneration of the 1957 event was possible.
- Model sensitivity and accuracy of simulation results were directly influenced by friction values mainly within the channel and the specific friction value was successfully identified through sensitivity analysis.

#### **7.1.4. Vulnerability and Risk Assessment**

- The vulnerability of the physical elements at risk can be identified using flood hazard maps and stage damage curves.
- It was possible to identify the effect of a flood event of intensity of 1957 on the present elements at risk using historical event data and present elements at risk data.
- The degree of risk in the area was possible to identify using qualitative measures in data poor environment such as in case of non-availability of economic value of the elements separately for different land use types. Furthermore the quantitative assessment of risk in monetary terms for economic value generation and its consequences on the present economy were also made possible.
- Risk curve for the area was an important input for the local authorities for making investment plans and also for the future prediction of average annual risk for flood events up to 1000 years.

#### **7.2. Recommendation for Future Study**

- Flood characteristics change if there is a change in the DEM interpolation and therefore it is one of the major issues for any flood modeling. The interpolation method of ANUDEM was considered to be sufficient for the scope of the study and the effect of different interpolation methods and accuracy assessment were left for further studies.
- The inclusion of the buildings in friction map instead of DSM directly is recommended for future studies.
- Data from several gauging station can be an added advantage for future studies which can look into flood routing. This can further be helpful for model calibration.
- With the level of data available for the elements at risk (up to individual building units) further studies of vulnerability assessment is possible which is recommended for future keeping the present study as a building block.
- A regional database should be evolved by integration of the historical and the current data for future study.

### **7.3. Recommendations for the Local Administrative Authorities**

- A renewed prevention plan is necessary for the implementation of the measures against disaster events appropriate for structural measures for planning purposes.
- The primary phase of risk assessment can facilitate the planning phase and an active Decision support system (DSS).
- Flood mitigation measures both conventional and non-conventional are recommended. Infrastructure for development of flood defense mechanism by construction and repairing of dykes (design and structural measures according to the present safety level), widening of riverbeds in areas where it is possible and also some spatial planning strategies for changing the type of land-use, construction of new buildings in safe zones , relocation of the elements at high risk to safer locations and development of early warning systems are some of the conventional measures which are suggested.
- It is essential to develop awareness among people and making them conscious about the damage potential of the area. There should be transparency in terms of risk communication between people and the authorities.
- There should be in improvement in the condition of preparation of PPR and not only the administrative units but local people should be involved in the definition of responsibilities of acceptable risks.



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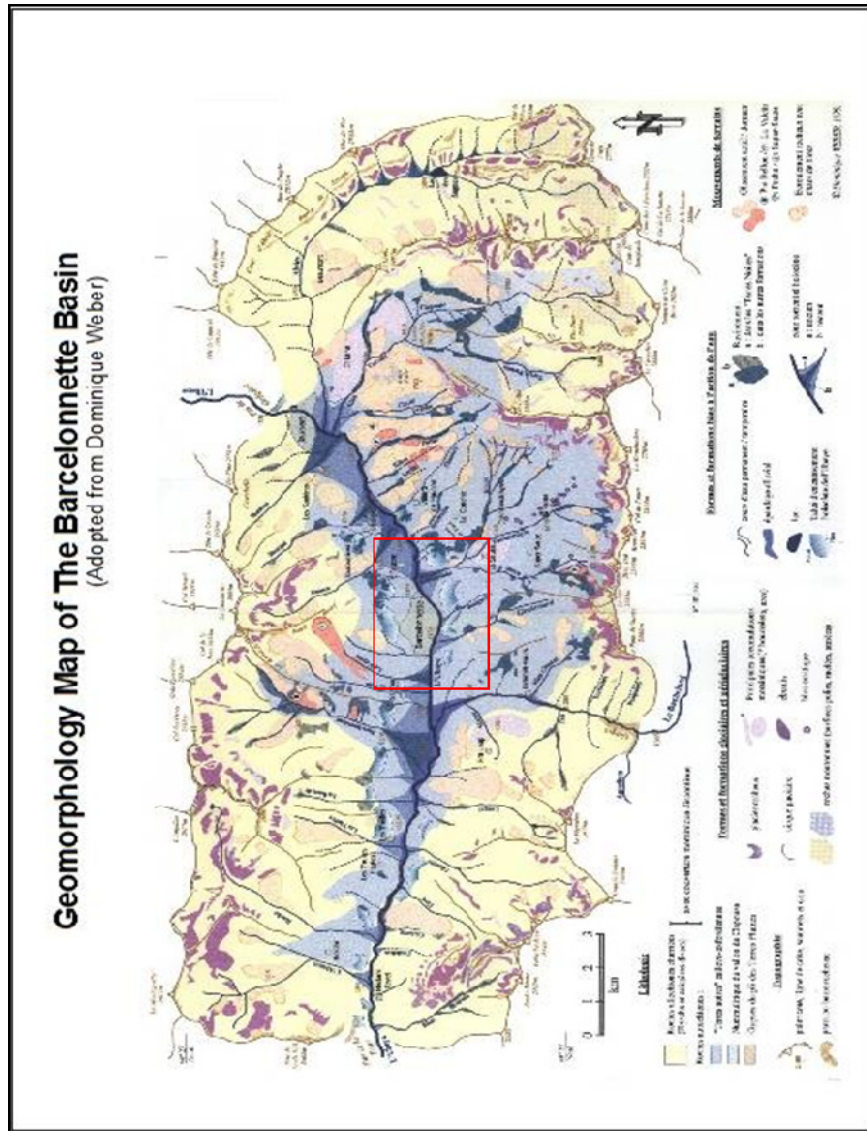
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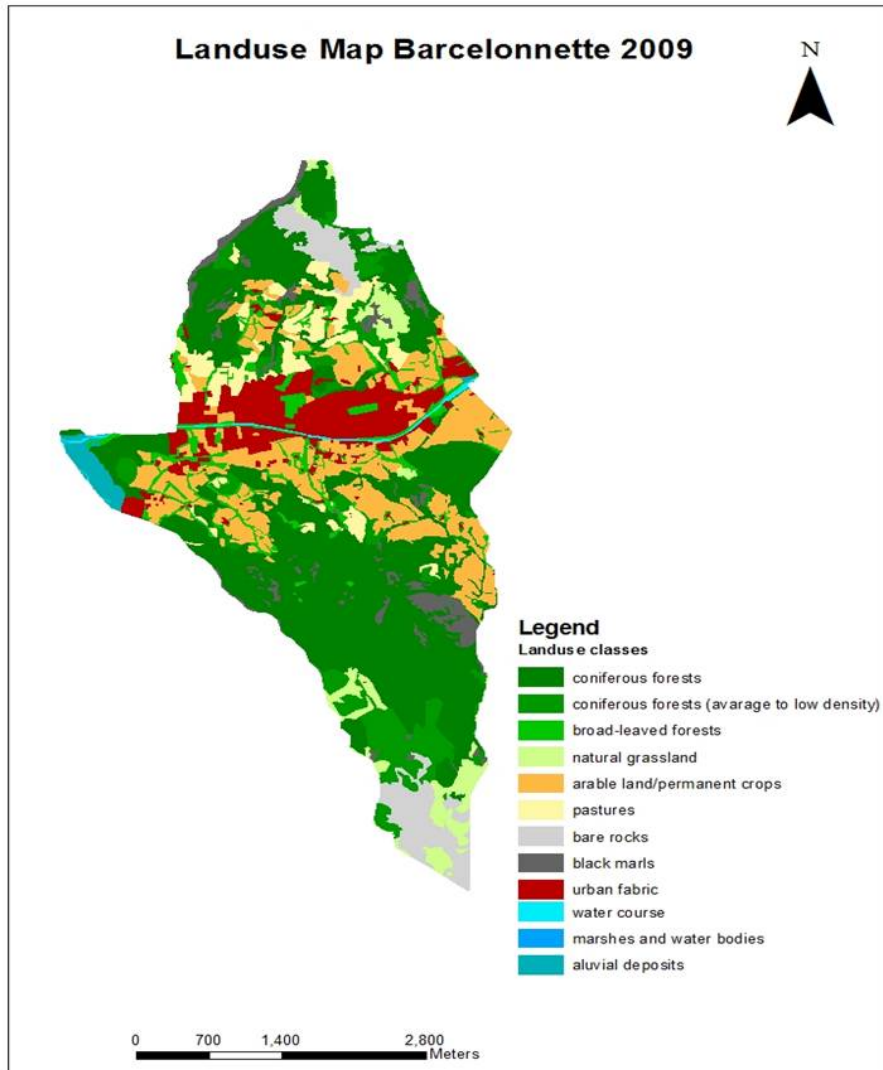
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Appendices

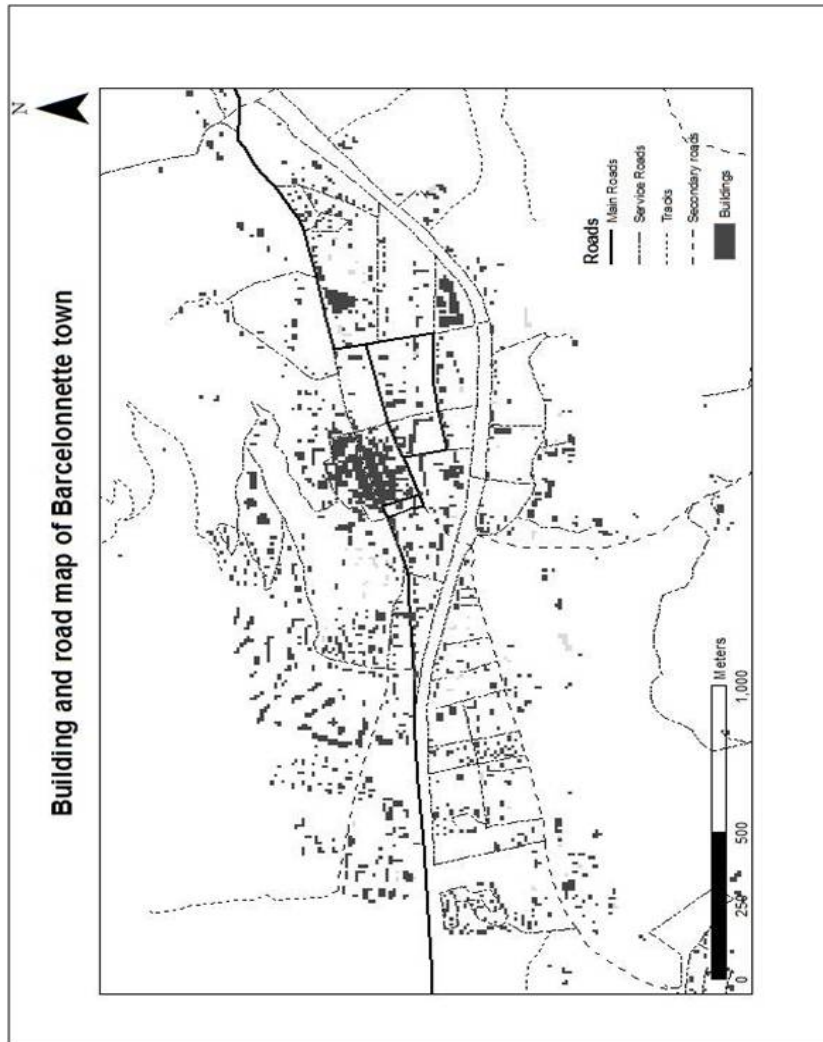
Appendix 1



## Appendix 2



Appendix 3



### Appendix 4.

Goodness of Fit - Summary						
#	Distribution	Kolmogorov	Anderson	Chi-Squared		
		Smirnov	Darling	Statistic	Rank	
Statistic	Rank	Statistic	Rank	Statistic	Rank	
1	Beta	0.29104	39	16.837	39	97.25
2	Burr	0.04994	2	0.33704	2	4.8016
3	Burr (4P)	0.04936	1	0.3277	1	5.8845
4	Cauchy	0.12368	20	2.3313	17	5.0237
5	Chi-Squared	0.30372	41	43.821	52	79.885
6	Chi-Squared (2P)	0.23503	28	12.835	32	77.486
7	Dagum	0.05299	3	0.3662	3	7.2149
8	Dagum (4P)	0.77143	55	161.07	55	587.97
9	Error	0.23801	31	11.225	29	56.016
10	Error Function	0.607	53	56.937	53	210.26
11	Exponential	0.27237	34	12.99	33	86.993
12	Exponential (2P)	0.23057	27	9.8362	27	56.058
13	Fatigue Life	0.13302	22	2.4743	18	14.736
14	Fatigue Life (3P)	0.13473	23	2.5081	19	15.416
15	Frechet	0.11317	16	2.021	14	11.045
16	Frechet (3P)	0.0857	11	5.2817	23	N/A
17	Gamma	0.30675	42	15.659	37	102.6
18	Gamma (3P)	0.15004	24	3.5831	20	18.821
19	Gen. Extreme Value	0.08189	9	1.5491	13	8.3457
20	Gen. Gamma	0.2364	29	9.1845	26	50.318
21	Gen. Gamma (4P)	0.11481	17	2.2219	15	15.028
22	Gen. Pareto	0.11548	18	31.228	50	N/A
23	Gumbel Max	0.2792	38	13.377	35	112.5
24	Gumbel Min	0.34057	45	22.806	43	N/A
25	Hypersecant	0.2597	32	12.7	31	86.834
26	Inv. Gaussian	0.27712	37	12.571	30	49.639
27	Inv. Gaussian (3P)	0.12856	21	2.2987	16	15.548
28	Kumaraswamy	0.31474	44	23.56	44	N/A
29	Laplace	0.23801	30	11.225	28	56.016
30	Ley	0.43467	51	27.107	48	168.19
31	Ley (2P)	0.39818	49	22.593	42	110.97
32	Log-Gamma	0.08763	12	1.2273	9	8.407
33	Log-Logistic	0.05386	4	0.51048	5	7.2427
34	Log-Logistic (3P)	0.05408	5	0.38279	4	7.7549
35	Log-Pearson 3	0.09754	15	5.1822	22	N/A
36	Logistic	0.26662	33	13.734	36	101.35
37	Lognormal	0.09672	14	1.3418	12	11.917
38	Lognormal (3P)	0.09643	13	1.338	11	9.7596
39	Normal	0.27591	35	17.294	40	119.35
40	Pareto	0.40838	50	29.04	49	136.58
41	Pareto 2	0.2769	36	13.278	34	85.285
42	Pearson 5	0.08528	10	1.2893	10	8.4256
43	Pearson 5 (3P)	0.08055	7	0.86171	7	9.0828
44	Pearson 6	0.08146	8	0.92043	8	9.0807
45	Pearson 6 (4P)	0.07983	6	0.85655	6	9.0827
46	Pert	0.43645	52	31.532	51	118.07
47	Power Function	0.37391	48	24.63	45	259.64
48	Rayleigh	0.18438	26	6.9509	25	27.373
49	Rayleigh (2P)	0.30308	40	15.934	38	64.731
50	Reciprocal	0.35886	46	20.898	41	149.44
51	Rice	0.37072	47	26.032	46	60.371
52	Student's t	0.9877	56	646.26	56	N/A
53	Triangular	0.6811	54	91.804	54	250.63
54	Uniform	0.31169	43	26.477	47	N/A
55	Weibull	0.12267	19	4.6984	21	8.0707
56	Weibull (3P)	0.16188	25	6.3351	24	44.673
57	Erlang	No fit				
58	Erlang (3P)	No fit				
59	Johnson SB	No fit				
60	Johnson SU	No fit				
61	Nakagami	No fit				

Appendix 5a.

Gumbel max without extreme events				Pearson 6 without extreme events			
Kolmogorov-Smirnov							
Sample size				102			
Statistics				0.65			
P-value				0.76			
Rank				12			
$\alpha$	0.2	0.1	0.05	0.02	0.01	0.2	0.1
Critical value	0.106	0.121	0.13	0.15	0.16	0.11	0.12
Reject?	No	No	No	No	No	No	No
Anderson-Darling							
Sample size				102			
Statistics				0.44			
Rank				8			
$\alpha$	0.2	0.1	0.05	0.02	0.01	0.2	0.1
Critical value	1.37	1.92	2.5	3.2	3.9	1.37	1.92
Reject?	No	No	No	No	No	No	No
Chi-squared							
Deg. Of Freedom							
Statistics							
P-value							
Rank							
$\alpha$	0.2	0.1	0.05	0.02	0.01	0.2	0.1
Critical value	8.55	10.65	12.59	15.09	16.81	8.5	10.6
Reject?	No	No	No	No	No	No	No

Appendix 5b

Global max without extreme events		Pearson 6 without extreme events	
<b>Kolmogorov-Smirnov</b>			
Sample size		102	
Statistics		0.65	
P-value		0.76	
Rank		12	
$\alpha$	0.2	0.1	0.05
Critical value	0.106	0.121	0.13
Reject?	No	No	No
<b>Anderson-Darling</b>			
Sample size		102	
Statistics		0.44	
Rank		8	
$\alpha$	0.2	0.1	0.05
Critical value	1.37	1.92	2.5
Reject?	No	No	No
<b>Chi-squared</b>			
Deg. Of Freedom		6	
Statistics		2.9	
P-value		0.81	
Rank		6	
$\alpha$	0.2	0.1	0.05
Critical value	8.55	10.65	12.59
Reject?	No	No	No
<b>F</b>			
Sample size		102	
Statistics		0.065	
P-value		0.74	
Rank		13	
$\alpha$	0.2	0.1	0.05
Critical value	0.106	0.121	0.13
Reject?	No	No	No
<b>Log-rank</b>			
Sample size		102	
Statistics		0.44	
Rank		8	
$\alpha$	0.2	0.1	0.05
Critical value	1.37	1.92	2.51
Reject?	No	No	No
<b>Mann-Whitney U</b>			
Sample size		102	
Statistics		0.44	
Rank		8	
$\alpha$	0.2	0.1	0.05
Critical value	1.37	1.92	2.51
Reject?	No	No	No
<b>Shapiro-Wilk</b>			
Sample size		102	
Statistics		0.44	
Rank		8	
$\alpha$	0.2	0.1	0.05
Critical value	1.37	1.92	2.51
Reject?	No	No	No
<b>T</b>			
Sample size		102	
Statistics		0.44	
Rank		8	
$\alpha$	0.2	0.1	0.05
Critical value	1.37	1.92	2.51
Reject?	No	No	No
<b>W</b>			
Sample size		102	
Statistics		0.44	
Rank		8	
$\alpha$	0.2	0.1	0.05
Critical value	1.37	1.92	2.51
Reject?	No	No	No

**Appendix 6:**

**Table showing the derived discharge data from Hydrographs of different return periods used for model simulation**

Discharge (m3/sec) (500 year event)	Discharge (m3/sec) (225 year event)	Discharge (m3/sec) (150 year event)	Discharge (m3/sec) (75year event)
0	0	0	0
50	30	30	30
100	75	60	50
150	130	100	75
200	120	130	100
300	130	150	110
350	150	190	120
400	200	225	135
450	230	240	140
550	280	280	155
600	320	310	165
790	350	300	170
950	375	290	180
650	390	275	175
500	400	250	160
450	425	230	145
400	450	220	120
375	420	200	100
320	400	180	90
250	370	165	85
230	330	150	70
180	260	120	60
150	190	100	50
100	130	80	40
80	70	50	30
50	50	30	30



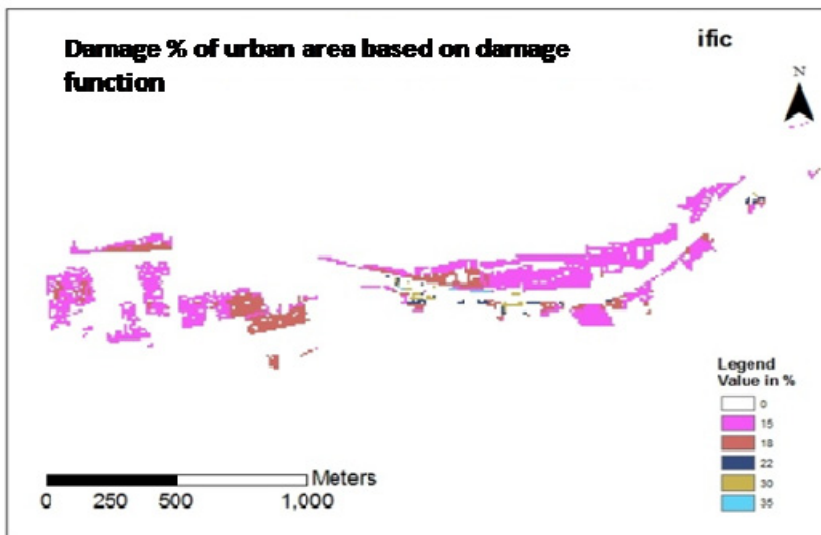
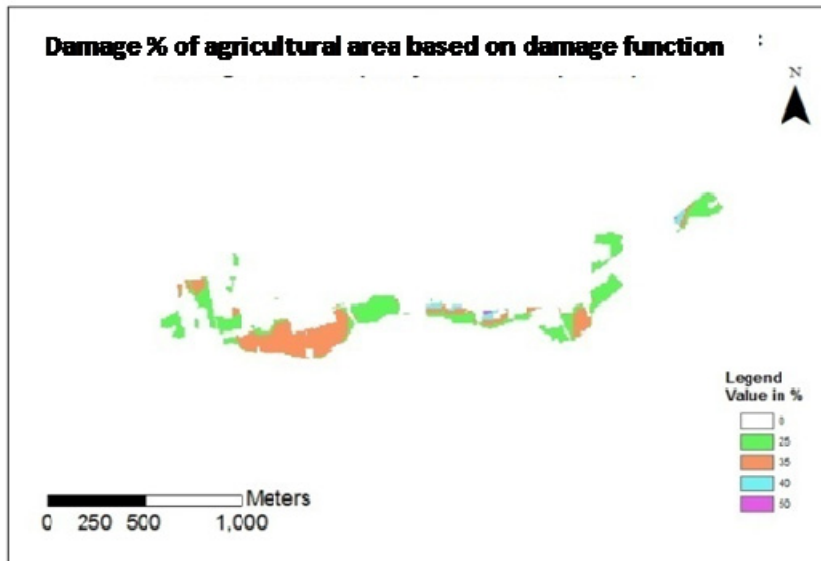
**Appendix 7. Time-series tables from SOBEK model**

PARAMETER	LOCATION	DATE	TIME	VALUE
Velocity (m/s)	1_119	6/16/1957	0	0.00000
Velocity (m/s)	1_119	6/16/1957	5	0.00000
Velocity (m/s)	1_119	6/16/1957	10	0.00000
Velocity (m/s)	1_119	6/16/1957	15	1.80245
Velocity (m/s)	1_119	6/16/1957	20	1.84112
Velocity (m/s)	1_119	6/16/1957	25	1.85043
Velocity (m/s)	1_119	6/16/1957	30	1.85603
Velocity (m/s)	1_119	6/16/1957	35	1.86262
Velocity (m/s)	1_119	6/16/1957	40	1.86913
Velocity (m/s)	1_119	6/16/1957	45	1.87554
Velocity (m/s)	1_119	6/16/1957	50	1.88191
Velocity (m/s)	1_119	6/16/1957	55	1.88810
Velocity (m/s)	1_119	6/16/1957	100	1.89428
Velocity (m/s)	1_119	6/16/1957	105	1.90037
Velocity (m/s)	1_119	6/16/1957	110	1.90640
Velocity (m/s)	1_119	6/16/1957	115	1.91225
Velocity (m/s)	1_119	6/16/1957	120	1.91840
Velocity (m/s)	1_119	6/16/1957	125	1.92411
Velocity (m/s)	1_119	6/16/1957	130	1.92989

PARAMETER	LOCATION	DATE	TIME	VALUE
Discharge (m³/s)	1_119	6/16/1957	0	0.00000
Discharge (m³/s)	1_119	6/16/1957	5	0.00000
Discharge (m³/s)	1_119	6/16/1957	10	0.00000
Discharge (m³/s)	1_119	6/16/1957	15	47.35842
Discharge (m³/s)	1_119	6/16/1957	20	50.84740
Discharge (m³/s)	1_119	6/16/1957	25	51.59015
Discharge (m³/s)	1_119	6/16/1957	30	52.17912
Discharge (m³/s)	1_119	6/16/1957	35	52.73999
Discharge (m³/s)	1_119	6/16/1957	40	53.29218
Discharge (m³/s)	1_119	6/16/1957	45	53.84388
Discharge (m³/s)	1_119	6/16/1957	50	54.39593
Discharge (m³/s)	1_119	6/16/1957	55	54.94001
Discharge (m³/s)	1_119	6/16/1957	100	55.48727
Discharge (m³/s)	1_119	6/16/1957	105	56.03198
Discharge (m³/s)	1_119	6/16/1957	110	56.57615
Discharge (m³/s)	1_119	6/16/1957	115	57.11263
Discharge (m³/s)	1_119	6/16/1957	120	57.66609
Discharge (m³/s)	1_119	6/16/1957	125	58.19470
Discharge (m³/s)	1_119	6/16/1957	130	58.73146

PARAMETER	LOCATION	DATE	TIME	VALUE
Waterdepth (m)	1_1	6/16/1957	0.00000	0.00100
Waterdepth (m)	1_1	6/16/1957	5.00000	1.36538
Waterdepth (m)	1_1	6/16/1957	10.00000	1.38171
Waterdepth (m)	1_1	6/16/1957	15.00000	1.39050
Waterdepth (m)	1_1	6/16/1957	20.00000	1.39890
Waterdepth (m)	1_1	6/16/1957	25.00000	1.40723
Waterdepth (m)	1_1	6/16/1957	30.00000	1.41552
Waterdepth (m)	1_1	6/16/1957	35.00000	1.42377
Waterdepth (m)	1_1	6/16/1957	40.00000	1.43198
Waterdepth (m)	1_1	6/16/1957	45.00000	1.44012
Waterdepth (m)	1_1	6/16/1957	50.00000	1.44822
Waterdepth (m)	1_1	6/16/1957	55.00000	1.45632
Waterdepth (m)	1_1	6/16/1957	100.00000	1.46434
Waterdepth (m)	1_1	6/16/1957	105.00000	1.47235
Waterdepth (m)	1_1	6/16/1957	110.00000	1.48031
Waterdepth (m)	1_1	6/16/1957	115.00000	1.48824
Waterdepth (m)	1_1	6/16/1957	120.00000	1.49612
Waterdepth (m)	1_1	6/16/1957	125.00000	1.50398
Waterdepth (m)	1_1	6/16/1957	130.00000	1.51179

Appendix 8: Intermediate maps for damage assessment



## Appendix 9.

Hazard classes based on PER

<b>Height of water (m)</b>	<b>Duration of flood (days)</b>	<b>Level of hazard</b>
0-1	1-2	Low
	3-4	Medium
	More than 4	High
1-2	1-2	Medium
	3-4	High
	More than 4	Very High
More than 2	1-2	High
	More than 2	Very High

Hazard classes based on PPR (qualitative)

<b>Height of water (m)</b>	<b>Flow velocity</b>	<b>Level of hazard</b>
Less than 0.5	Low	Low
	Medium	Medium
	High	High
0.5-1	Low	Medium
	Medium	High
	High	Very High
More than 1	Medium	High
	High	Very High