



Deterministic hydrological modeling for flood risk assessment in large urban environments: application to Mexico City

Rafael Vargas Bringas

► To cite this version:

Rafael Vargas Bringas. Deterministic hydrological modeling for flood risk assessment in large urban environments: application to Mexico City. Other. Université Côte d'Azur, 2016. English. NNT : 2016AZUR4115 . tel-01488436

HAL Id: tel-01488436

<https://theses.hal.science/tel-01488436>

Submitted on 13 Mar 2017

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

UNIVERSITY OF NICE SOPHIA ANTIPOLIS
STIC DOCTORAL SCHOOL
INFORMATION AND COMMUNICATION SCIENCES

T H E S I S

submitted for the degree of

Doctor of Science

Of University of Nice-Sophia Antipolis

Mention: Automatic, Signal and Image Processing

presented by

Rafael VARGAS

Deterministic hydrological modeling for flood risk assessment in large urban environments: Application to Mexico City.

Thesis directed by *Philippe GOURBESVILLE*

Presented on December 9th, 2016

Jury:

Rapporteur : Monsieur Liong, Shie Yui

Rapporteur : Monsieur Gomez Valentin, Manuel

Examiner : Monsieur Audra, Philippe

Examiner : Monsieur Delestre, Olivier

Examiner: Monsieur Gourbesville, Philippe

Thesis director : Prof. Philippe Gourbesville



UNIVERSITE NICE SOPHIA ANTIPOLIS
ECOLE DOCTORALE STIC
SCIENCES ET TECHNOLOGIES DE L'INFORMATION ET DE LA COMMUNICATION

THESE

pour l'obtention du grade de

Docteur en Sciences

de l'Université de Nice-Sophia Antipolis

Mention: Automatique, Traitement du Signal et des Images

présentée et soutenue par

Rafael VARGAS

**Modélisation hydrologique déterministes pour l'évaluation des
risques d'inondation dans les grands environnements urbains:
Application à Mexico.**

Thèse dirigée par *Philippe GOURBESVILLE*

Soutenue le 09 Décembre, 2016

Jury:

Rapporteur : Monsieur Liong, Shie Yui

Rapporteur: Monsieur Gomez Valentin, Manuel

Examineur : Monsieur Audra, Philippe

Examineur : Monsieur Delestre, Olivier

Examineur: Monsieur Gourbesville, Philippe

Directeur de thèse Prof. Philippe Gourbesville



Innovative CiTy Lab



POLYTECH
NICE-SOPHIA

ABSTRACT

According to the World Risk Report released by the United Nations University Institute for Environment and Human Security, Mexico has a vulnerability of 46% and a lack of coping capacity of 76% in terms of disaster risk. One of those disaster risks is flooding which poses a serious challenge to the development and the lives of the inhabitants of Mexico.

Mexico City is facing problems of flooding in some areas at certain times of the year, causing important losses and damages on properties and residents including some casualties. Therefore, it is important to carry out a flood risk assessment in the catchment of Mexico City and estimate damages of probable flood events.

However, limited data of observed discharges and water depths in the main rivers of the city are available, and this represents an obstacle for the understanding of flooding in Mexico City. For these reason, several studies have to be carried out in order to have a clear understanding of the catchment, which involve, meteorological and hydrological/hidraulic studies, rainfall distribution, runoff analysis, flood risk and vulnerability, and this studies allow the estimation of direct and indirect damages to the economy, to assets and to human life.

The premise of this study is that with the limited data and resources available, the catchment can be represented to an acceptable degree by the construction of a deterministic hydrological model of the Mexico City basin. The objective of the developed tool is to provide an efficient support to management of the flood processes by predicting the behavior of the catchment for different rainfall events and flood scenarios. Therefore, after obtaining the resulting discharges form the hydrological model in MIKE SHE software, these were used to carry out a flood hazard assessment. The discharges in 7 rivers and the water level downstream were input in MIKE 21 software as discharge boundaries for the model with the aim of assessing the extent of the areas of flood risk and the flood depth in Mexico City. In addition, a grid size sensitivity analysis was carried out for the topography used in MIKE 21. Grid sizes of 50

Abstract

m, 30 m and 20 m were used in a MIKE 21 model to create flood maps and analyze the differences in flood extent and depth.

In addition, research was carried out regarding the different approaches existing worldwide for the estimation of direct and indirect damages, and an estimation of damages to several types of buildings was made for one of the simulated flooded areas of Mexico City.

RESUME

Selon le Rapport mondial des risques publié par l'Institut universitaire des Nations Unies pour l'environnement et la sécurité humaine, le Mexique a une vulnérabilité de 46% et un manque de capacité d'adaptation de 76% en termes de risques de catastrophe. Un de ceux est les risques d'inondation en cas de catastrophe qui pose un sérieux défi pour le développement et la vie des habitants du Mexique.

Mexico est confronté à des problèmes d'inondation dans certaines zones à l'ONU certaines périodes de l'année, causant des pertes et des dommages importants sur les propriétés et les résidents dont certains blessés. En conséquence, il est important de procéder à une évaluation des risques d'inondation dans le bassin de Mexico et d'estimer les dommages des inondations probables.

Cependant, les données limitées de débits observés et des profondeurs d'eau dans les principaux cours d'eau de la ville sont disponibles, et cela constitue un obstacle à la compréhension des inondations dans la ville de Mexico. Pour la raison d'origine, plusieurs études doivent être effectuées intérêt dans le but d'avoir une compréhension claire disponibles du bassin versant, qui impliquent, études hydrauliques, météorologiques et hydrologiques, la répartition des précipitations, l'analyse des eaux de ruissellement, les risques d'inondation et de la vulnérabilité, et des études de cela permettent l'estimation de dommages directs et indirects à l'économie, aux actifs et à la vie humaine.

La prémisse de l'étude est que, avec ces données et les ressources limitées disponibles, le bassin peut être représentée à un niveau acceptable par la construction d'un modèle hydrologique déterministe du bassin de Mexico. L'objectif de l'outil développé est de fournir un soutien efficace à la gestion des processus d'inondation en prédisant le comportement du bassin versant pour différents événements de précipitations et les scénarios d'inondation. Par conséquent, après obtention de la forme résultant des rejets dans le modèle logiciel MIKE SHE hydrologique, en d'origine ont été utilisés pour effectuer une évaluation des risques d'inondation. Les décharges dans sept rivières et le niveau de l'eau en aval ont été saisies dans le logiciel MIKE 21

Résumé

que les limites de rejet pour le modèle dans le but d'évaluer l'étendue des domaines de risques d'inondation et de la profondeur d'inondation dans la ville de Mexico. En outre, une analyse de sensibilité de taille de la grille a été réalisée intérêt dehors pour la topographie utilisé dans les tailles MIKE 21.

En outre, la recherche a été effectuée sur l'intérêt approches existantes concernant les différentes dans le monde entier pour l'estimation des dommages directs et indirects, et on propose une méthode pour l'analyse des dommages à Mexico et dans d'autres parties du pays.

Avec les résultats de modèle d'inondation MIKE 21, il était une analyse des dommages économiques directs. Pour cela, le nombre de bâtiments de différents types ont été quantifiée dans une zone définie. Une équation de dommages dus aux inondations a été utilisé pour estimer les dommages aux maisons. valeurs par mètre carré de construction pour estimer les dommages économiques ont été utilisés dans le cas des autres types de bâtiments. Total des dommages ont été ajoutés. Les résultats ont été analysés et discutés, aussi des incertitudes. Recommandations pour les études futures sont écrites dans les conclusions.

ACKNOWLEDGEMENTS

I want to thank God first and foremost for the many blessings I have received including the possibility to do a PhD in the Universite de Nice, France.

I thank my parents and brother for their support all throughout my studies, for their love and understanding.

A special thank to Prof. Dr Philippe GOURBESVILLE, who guided, supported and encouraged me to carry out my research. This allowed me to complete my work successfully and solve difficulties I found along the way. His suggestions and corrections were greatly appreciated as well as the review of my thesis progress. I hope to remain in a long relation of work and friendship in the future.

All colleagues at Innovative-City Lab deserve a special thanks as well, and the people at the Mediterranean Institute of Risk Environment and Sustainable Development who supported. In particular, I would like to thank to Mae Brigitt Bernadel VILLORDON, Duong VO and Thi Kim Lien TRAN for their friendship during the thesis period.

Also I recognize the staff of Polytech'Nice Sophia, STIC PhD School, University of Nice Sophia Antipolis who helped in the administration over my PhD, in particular to Mrs Annie VAHRAMIAN, Mr Fabrice LEBAS, Mr Ali Beikbaghban.

In addition, I thank the people at the national council of science and technology of Mexico (CONACYT) for the financial support, the people at the geography and statistics institute (INEGI) for the spatial data, the water commission (CONAGUA) for hydro-meteorological data.

The national university (UNAM) allowed me to consult and copy part of their articles and books in hydrology, which was a great source of information for my thesis.

Moreover, I want to thank the department of surface waters in CONAGUA, where I found support to find the rainfall data, and where I received only positive replies in my searches.

Professor Carlos Diaz, and Prof. Baro Suarez who are working in the inter-american center of water resources (CIRA), deserve special recognition in my work, as they were

Acknowledgements

always willing and available to offer technical guidance in the subject of economic flood damage.

The methodology they developed was useful when estimating damages in the catchment of Mexico City.

TABLE OF CONTENTS

ABSTRACT	4
RESUME	6
ACKNOWLEDGEMENTS	8
TABLE OF CONTENTS	10
LIST OF FIGURES	16
LIST OF TABLES.....	22
Chapter 1 INTRODUCTION	24
1.1 Floods & cities.....	24
1.1.1 Pluvial floods	25
1.1.2 Riverine floods.....	27
1.1.3 Flash floods	28
1.1.4 Coastal floods.....	29
1.2 Exposure	31
1.3 Vulnerability.....	31
1.3.1 Physical vulnerability of people and infrastructure	32
1.3.2 Unfavourable organizational and economic conditions	32
1.3.3 Attitudes and motivations	32
1.4 Concept of risk management	33
1.5 Situation in Mexico City.....	33
1.6 Hydrological models for flood inundations assesment.....	40
1.6.1 Model selection criteria.....	42
1.6.2 MIKE SHE Model.....	45
1.6.3 MIKE SHE architecture.....	48
	10

Table of contents

1.6.4 MIKE SHE performance in past studies.	58
1.6.5 Runoff modeling.	62
Chapter 2 FLOOD HAZARDS, VULNERABILITY AND RISKS.	65
2.1 Flood risk.....	65
2.2 Flood risk management.....	67
2.3 Maturity levels.	68
2.4 Vulnerability and resilience.	72
2.5 The flood modeling process.....	72
2.5.1 Objectives.....	73
2.5.2 Type of maps.....	74
2.6 Modeling approach and data availability.....	74
2.7 Data needs and availability	75
2.8 Required capacity	76
2.9 Flood hazard assessments using Topographical LiDAR datasets.....	78
2.9.1 DEM data sources.....	80
2.9.2 Topography grid size sensitivity analysis.	82
2.10 1-D and 2-D flood hazard models	88
2.11 Vulnerability and risk mapping	89
2.11.1 Flood risk maps	92
2.11.2 Considerations for flood risk mapping	93
2.11.3 Determination of flood zones.....	95
2.11.4 Determination of appropriate land uses.	96
2.12 Direct impacts of flooding.....	97
2.12.1 People	97
2.12.2 Buildings and contents	99
2.13 Indirect impacts of flooding	101
2.13.1 Natural environment	102

Table of contents

2.13.2 Human and social impacts	103
2.13.3 Demographic changes	103
2.13.4 Health impacts.....	103
2.13.5 Human development impacts.....	105
2.13.6 Impact on long-term economic growth.	105
2.13.7 Impact on development goals	105
2.13.8 Impact on livelihoods.....	106
2.13.9 Business interruption.....	106
2.14 Assessment and prioritization of needs	106
2.15 Mitigating damages.....	107
2.15.1 Structural measures to prevent or reduce floods	108
2.15.2 Non-structural flood mitigation measures.....	111
2.15.3 Impact of river control structures	114
2.15.4 Examples of mitigating measures in Mexico.	115
2.15.5 Case of the Gaviotas Sur neighborhood, Villahermosa, Mexico.	119
2.15.6 Proposal of alternatives.....	123
Chapter 3 MEXICO CITY CATCHMENT AND FLOOD PROCESSES.....	125
3.1 Mexico City catchment.....	125
3.1.1 General.....	125
3.1.2 Water supply in Mexico City	127
3.1.3 Description of the Mexico City aquifer and its exploitation	128
3.1.4 Hydrologic zones	130
3.1.5 Water level declines in the aquifer and land subsidence.	132
3.1.6 Water sustainability in the Mexico City catchment.	139
Chapter 4 HYDRO-METEOROLOGICAL DATA IN MEXICO.....	143
4.1. Meteorological data.....	143
4.1.1 Methods to obtain the rainfall distribution.....	144

Table of contents

4.1.2 Analysis of rainfall.....	145
4.1.3 The Climatological Data Base of Mexico (BDCN)	147
4.2 Physiographic and hydrological data	149
Chapter 5 THE MODELING APPROACH: STRATEGY, DATA AND APPLICATION ...	153
5.1 Deterministic hydrological model of Mexico City.....	154
5.1.1 Methodology	154
5.1.2 Description of catchment.	160
5.1.3 Application to Mexico City Basin.	163
5.1.4 Development of 3 study cases.	164
5.1.5 Results.....	173
5.2 Flood hazard mapping with 2D hydraulic modeling	178
5.2.1 Application of MIKE 21.	178
5.2.2 Results.....	179
5.3 Topography grid size sensitivity analysis.	183
5.4 Flood hazard analysis of buildings.....	187
5.5 Conclusions about modeling approach and results.	192
Chapter 6 ECONOMIC FLOOD DAMAGES	198
6.1 Flood damage.	198
6.1.1 General.....	198
6.1.2 Types of flood damage.....	200
6.1.2 Actual and potential damages:	202
6.1.3 Methods for estimation of direct economic flood damages	203
6.2 Land use data	206
6.2.1 Aggregated land use data	208
6.2.2 Other data.....	208
6.3 Determination of the value of assets at risk	209

Table of contents

6.4 Calculation of economic damage.....	210
6.4.1 Stage–damage curves	211
6.5 Estimation of flood damage for a flooded area of Mexico City.....	214
6.5.1 Damage to housing.	214
6.5.2 Damage to buildings.....	219
Chapter 7 ANALYSIS OF UNCERTAINTIES	223
7.1 Possible quality problems of the rainfall data in Mexico	223
7.1.1 Potential problems in homogeneity	224
7.1.2 Possibility of delay problems.	224
7.2 Uncertainties in streamflow simulations	225
7.3 Uncertainty in the gauged discharge data.	226
7.4 Uncertainties in flood damage assessments	226
Chapter 8 CONCLUSIONS AND PERSPECTIVES	229
8.1 Conclusions.....	229
8.1.1 Hydrological model.....	229
8.1.2 Flood hazard mapping in 2D modeling.....	231
8.1.3 Grid size sensitivity analysis.....	232
8.1.4 Flood control and mitigation	232
8.2 Perspectives.....	232
REFERENCES	234
APPENDIX	245
Appendix I. Climatological stations.	245
Appendix II. Discharge gauging stations.....	251
Appendix III. Code for converting from .sdf to .xns11 (HEC-RAS to MIKE 11) for cross section data (Created by Vo Ngoc Duong, of The University of Da Nang, Vietnam).	

LIST OF FIGURES

Figure 1.1. The influence of urbanization on different components of the water cycle. [USDA, 2010].....	25
Figure. 1.2 Vehicle trapped in flood water, in Wallington, London. [Floodlist, 2016]	26
Figure 1.3 The Eel River flooding across CA Hwy 211 [California Gov, 2016].....	27
Figure 1.4 Men collect their belongings from a makeshift shop after a flash flood caused by heavy rain on the outskirts of Peshawar, Pakistan [Newsweek, 2016].....	28
Figure 1.5 Coastal levees protecting Arcata waste water ponds from Humboldt Bay, California. Without levees protecting them, the waste water ponds flooded frequently. [California Gov, 2016].....	29
Figure 1.6 Risk management cycle. [Renn, 1992].....	32
Figure 1.7 Urban expansions from 1910 to 2000 in Mexico City. [Wikimedia, 2012]	33
Figure 1.8 Urban expansion in the West of Mexico City due to improper land use planning. [Dailymail, 2010].....	34
Figure 1.9 Uncontrolled urban growths in the Mexico City outskirts. [INEGI, 2016]	35
Figure 1.10 River Mixcoac flows from West to East and is encased from the point where it reaches a heavily populated area. [Google Earth, 2016].....	36
Figure 1.11 Annual rainfall in Distrito Federal, 1877-1997, (mm per year) [SMA-DF, 2006].....	38
Figure 1.12 The watershed as a hydrologic system [Chow et al., 1988]	41
Figure 1.13 Schematic of MIKE SHE model [DHI, 2012e].	48
Figure 1.14 Vertical discretization in unsaturated zone. [DHI, 2012e].....	52
Figure 1.15 Surface runoff, sub-surface runoff and underground runoff or baseflow. [UCAR, 2012].....	62
Figure 2.1 Steps of flood mapping process. [WMO and GWP, 2013]	72

List of figures

Figure 2.2 The capacity requirements for flood assessment and map development. [WMO and GWP, 2013].....	75
Figure 2.3 Aircraft surveying LiDAR topographic data. [NOAA, 2015]	78
Figure 2.4 A LiDAR image created with data collected by the National Geodetic Service. [NOAA, 2015].....	78
Figure 2.5 Maximum inundation area variation with DEM resolutions. [Haile, A., & Rientjes, T., 2005].....	82
Figure 2.6 Maximum flood depths for 5 m resolution.	83
Figure 2.7 maximum flood depths for 15 m. Resolution. [Haile, A., & Rientjes, T. ,2005].	83
Figure 2.8 Flood maps generated from different resolution DEMs [Saksena, 2014]	85
Figure 2.9 Economic losses in US billions and deaths worldwide. [Du et al., 2010]	96
Figure 2.10 Depth damage curve for one story residence with basement. [USACE, 1988].....	99
Figure 2.11 A gully caused by soil erosion in Mexico. [Jha et al. 2012]	101
Figure 2.12 Accumulation of sediments in dams. [Maeck et. Al, 2013]	109
Figure 2.13 Irregular occupation of federal land in Mexico City. [Milenio, 2016]	115
Figure 2.14. An example of how some houses have been built in low laying flood plains. [CNA, 2011].	117
Figure 2.15 An example of how to build houses in flood plains in medium altitude areas. [CNA, 2011].	118
Figure 2.16 Gaviotas Sur neighborhood in the city of Villahermosa.[Wikimapia, 2013]	118
Figure 2.17 Sports fields in the floodplain of the Santa Catarina River in Monterrey, Mexico [CNA, 2011].....	120
Figure 2.18 Map of the City of San Luis Potosi and River Santiago Blvd. [Google, INEGI, 2016]	121
Figure 2.19. Boulevard on the river Santiago. [CNA, 2011]	121
Figure 3.1 A view of the Grand Drainage Canal (Gran Canal Desague), which carries wastewater and stormwater runoff from the Mexico City Metropolitan Area. The canal	

List of figures

exits the Basin of Mexico through the Tequisquiac tunnel and empties into the Moctezuma River, a tributary to the Panuco River, which flows into the Gulf of Mexico. [Luege, 2012].....	126
Figure. 3.2 Interpretation of the historic ground water flow system in the Basin of Mexico City. Infiltration of precipitation and snow melt in the surrounding mountains forms a deep water table (A) with downward gradients, some of which exits at shallow water tables (Bi) in the lower foothills or piedmont regions, and the majority flows under the valley floor and upward through the clays as diffuse discharge (Bii) and as thermal springs (Biv) through fractures in the deep aquifer. All discharge from the closed basin is by evapotranspiration [Durazo and Farvolden, 1989]	128
Figure 3.3 Hydrologic zones of the Basin of Mexico. The lacustrine zone occupies the lower elevations of the basin (clear). The piedmont region, or transition zone, occurs on the lower and upper slopes. The two highest elevation classes roughly correspond to the mountain zone. [NAS, 1995].....	129
Figure 3.4 Mexico City aquifer. (1) The southern portion of the basin, exploited for ground waters as of 1995 (2) alluvial fill, (3) Pleistocene and more recent basalt including Sierra Chichinautzin, (4) Tarango formation, (4a) high mountain range, (5) volcanic hills and deposits, (6) stratified volcanic deposits, (7) Pliocene mountain range, (8) Pliocene lower lacustrine deposits, (9) Miocene volcanic deposits, (10) and (10a) Oligocene volcanic deposits, (11a) and (11b) Cretaceous limestone platform. The upper portion of the main aquifer is composed of units (2), (3), and (4). The lower portion of the main aquifer is composed of unit (6). Units (9), (10), and (11) are considered lower aquifers distinct from the main aquifer in exploitation. [Mooser, 1990]	130
Figure 3.5 A well casing rising about 7 meters above the ground in a Mexico City neighborhood [Lesser-Illades et al. 1990].	132
Figure 3.6 Progressive sinking of the city relative to the Grand Drainage Canal [NAS, 1995].....	134
Figure 3.7 Comparative subsidence in the city center area of Mexico City and the Chalco plain from about 1935 to the present. [Ortega et al. 1993].....	135
Figure 3.8 Water pump showing the soil subsidence. [Luege, 2012]	136
Figure 3.9 Internal deterioration of the Central Drain. [Luege, 2012]	138

List of figures

Figure 3.10. East Drain. View of the final lining work with slipform. [Luege, 2012]	139
Figure 3.11 Construction of the wastewater treatment plant in Atotonilco. [Luege, 2012]	140
Figure 4.1 Hydrometric station in the state of Hidalgo. [CNA, 2011]	149
Figure 4.2 Hydrometric station in the state of Puebla. [CNA, 2011]	150
Figure 5.1. Methodology for estimating the flood hazard in Mexico City.	153
Figure 5.2 MIKE 11 Branches and H_points in a MIKE SHE Grid with River Links (DHI, 2012).....	156
Figure 5.3 A typical simplified MIKE SHE river link cross section compared with the equivalent MIKE11 cross section (DHI 2012).....	157
Figure 5.4 The Mexico City catchment: Its location in the country of Mexico, the river network and the city limits.....	159
Figure 5.5 The Hondo River sub-catchment in the Mexico City catchment in white. ...	160
Figure 5.6 Distribution of the types of soils used in the hydrological model.	162
Figure 5.7 The Mexico City catchment and the hydro meteorological network.	163
Figure 5.8 Thiessen polygon distribution and average daily rainfall for 44 climatological stations in the Mexico City catchment.	165
Figure 5.9 Location of Hondo sub-catchment in the Mexico City catchment.....	167
Figure 5.10 River Hondo sub-catchment with hydro-meteorological network.	167
Figure 5.11 Distribution of Strickler coefficient in Hondo catchment according to land use.....	168
Figure 5.12 Thiessen polygon rainfall distribution of 5 stations in Hondo River sub- catchment.	169
Figure 5.13 Boundaries of the 6 different types of soils used in the River Hondo set-up.	170
Figure 5.14 Molino Blanco station simulated discharge against observed discharge for the Mexico City catchment model (1981).	173
Figure 5.15 St. Teresa station simulated discharge against observed discharge for the Mexico City catchment model (1981)	173

List of figures

Figure 5.16 Molino Blanco simulated discharge against observed discharge Hondo sub-catchment model including the effects of vegetation in Strickler coefficient (1981).	174
Figure 5.17 Molino Blanco station simulated discharge against observed discharge in Hondo River catchment model with unsaturated zone and land use components (1981).	174
Figure 5.18 Molino Blanco station simulated discharge in Hondo River catchment model with unsaturated zone and land use components for a period of 5 years.	175
Figure 5.19 Maximum water depth using topography of 50 m of grid size.	179
Figure 5.20 Maximum water depth using topography of 30 m of grid size.	180
Figure 5.21 Maximum water depth using topography of 50 m grid size.	183
Figure 5.22 Maximum water depth using topography of 30 m grid size.	184
Figure 5.23 Maximum water depth using topography of 20 m grid size.	185
Picture 5.24 Informal Settlements affected by flooding. (UN-HABITAT)	188
Figure 5.25 In order to analyse the flood hazard of some building types in Mexico City, the flooded area contained in the red circle was assessed.	189
Figure 5.26. Buildings affected by flooding simulated in MIKE 21 with a 20 m grid size.	191
Figure 5.27 Flooded area where the Remedios channel enters the reservoir East of the airport.....	192
Figure 5.28 Southern flooded area where the Remedios channel enters the reservoir at the East of the airport, with points of hypothetical channel failure. [CONAGUA, 2011]	193
Figure 5.29 Northern flooded area where the Remedios channel enters the reservoir at the East of the airport, with point of hypothetical channel failure. [CONAGUA, 2011]	194
Figure 5.30. Comparison of simulated flood in Remedios channel using MIKE 21 with images of flood extent created by CONAGUA.	195
Figure 6.1. Perturbation of an economic system hit by a flood. [Messner et.al, 2007]	200
Figure 6.2 The relationship between actual and potential damages. [Reproduced from Read Sturgess and Associates, 2000]	201
Figure 6.3 Example from the UK for Depth-Damage-Duration Data for Residential Properties [Penning-Rowsell et al. 2003]	205

List of figures

Figure 6.4. Potential damage for 5 types of housing in Mexico and for 5 intervals of flood depth. [Baró et.al, 2007b]	214
Figure 6.5 The flooded area contained in the red cyrcle was assessed.....	215
Figure 6.6 National inventory of housing in Mexico created by INEGI. [INEGI, 2016] ..	216
Figure 6.7 Example of the number of housing units in the flooded area of study. [INEGI, 2016].....	217
Figure 6.8. Example of number of inhabitants in flooded area of study. [INEGI, 2016]	217
Rainfall stations and evaporation stations in red.	244

LIST OF TABLES

Table 1.1. Factors contributing to flooding. [(WMO) and (GWP), 2013]	24
Table 1.2a Standard for model selection proposed by the WMO [Wittwer, 2013]	43
Table 1.2b Standard for model selection proposed by WMO [Wittwer, 2013]	44
Table 2.1: Maturity levels of flood risk management at city scale [Batika, Gourbesville, Tessier, 2013]	68
Table 2.2 Maturity levels for existing flood management frameworks in European and Asian case studies [Batika, Goubesville and Tessier, 2013].	70
Table 2.3 Types of vulnerability and the factors affecting their rate of exposure [Jha et al. 2012]	90
Table 2.4 Vulnerability assessment methods at different scales: [Villagran de Leon 2006]	91
Table 2.5 Considerations for flood risk mapping [Jha et al. 2012]	93
Table 2.6 Types of assessments after a flood. [Jha, 2010]	106
Table 3.1 Drainage networks in the Valley of Mexico are insufficient. [Luege, 2012] ..	137
Table 4.1 Basin classifications by size. [Chow, 1964]	145
Table 5.1 Values for the control of time steps during the MIKE SHE simulation.	171
Table 5.3 Maximum discharges recorded for Molino Blanco station in the 1979-1983 period and maximum discharge simulated.	176
Table 5.4 Statistical flood areas corresponding with flood depth and grid size for flood event of September 1981.	186
Table 5.5 Buildings types affected by flooding in the neighborhoods of Altavilla, San Miguel Jalostoc, 25 de Julio, El coyol, Arcos Esmeralda, Atzacolco and González Romero, and the flood depth for each building type.	190

List of tables

Table 6.1. Types of flood damages and examples. (Penning-RowSELL et al. 2003; Smith & Ward 1998).....	200
Table 6.2 Parameters affecting flood damage and their individual relevance. [Messner et al. 2007].....	204
Table 6.3 Overview of different land use data types [Meyer, 2005]	208
Table 6.4 Building types, quantities, flood depth and value per square meter. [Neodata, 2016].....	219
Table 6.5. Total damage to each building type, for a determined area of construction, and for ground floor only.....	219
Table 6.6. Total damage to each building type.....	220

Chapter 1

INTRODUCTION

1.1 Floods & cities.

A flood is considered a flow or invasion of excess water by surface runoff or by the accumulation of these on flat lands caused by a lack or insufficiency of both natural and artificial storm drain. The magnitude of a flood caused by hydro-meteorological events is dependent on the intensity of the rain, its distribution in space and time, on the size of the affected watersheds, on the characteristics of the soil, and on the natural and artificial drainage of basins. (Bremer and Lara, 2001).

Floods can be generally characterized into fluvial floods, pluvial floods, coastal floods, groundwater floods or the failure of artificial water systems. Based on the speed of onset of flooding, floods are often described as flash floods, urban floods, semi-permanent floods, and slow rise floods. All the mentioned types of floods can have severe impacts on urban areas, and thus be categorized as urban floods. It is important to understand both the cause and speed of onset of each type to understand their possible effects on urban areas and how to mitigate their impacts. [CNA, 2011]

The urban environment is subject to the same natural forces as the natural environment and the presence of urban settlements exacerbates the problem of flooding. Furthermore, in cities and towns, areas of open soil that can be used for water storage are very limited. High intensity rainfall can cause flooding when drainage systems do not have the necessary capacity to cope with flows and sometimes the water enters the sewage system in one place and resurfaces in others. [CNA, 2011]

Floods usually result from a combination of meteorological and hydrological extremes, as seen in the table below.

However they can also be caused by human activities. For example, unplanned growth and development in floodplains, the breach of a dam or the overtopping of an embankment can cause flooding. In several regions of the world, millions of people

have been moving from rural areas to cities in the last decades, and often settle in areas that are highly exposed to flooding. [CNA, 2011]

Meteorological factors	Hydrological factors	Human factors.
<ul style="list-style-type: none">• Rainfall• Cyclonic storms• Small-scale storms• Temperature• Snowfall and snowmelt	<ul style="list-style-type: none">• Groundwater level• Soil moisture level• Surface infiltration rate• Impervious cover• Channel cross-sectional shape and roughness• Presence or absence of over-bank flow, channel network• Synchronization of runoffs from various parts of watershed• High tide impeding drainage	<ul style="list-style-type: none">• Land-use changes• Occupation of the flood plain obstructing flows• Inefficiency or non maintenance of infrastructure• Urban microclimate may enforce precipitation events

Table 1.1. Factors contributing to flooding. [(WMO) and (GWP), 2013]

As a result of different combinations of causal factors, urban floods can be divided into four categories:

- Pluvial Floods
- Riverine Floods
- Coastal Floods
- Flash Floods

Floods in urban areas can be attributed to one or a combination of the above types. [WMO and GWP, 2013]

In order to manage urban floods it is important to understand the causes and impacts of each type.

1.1.1 Pluvial floods

These are of very high rainfall intensity and duration during the rainy season, sometimes caused by seasonal storms and depressions and exacerbated by saturated or impervious soils. Built environments like cities generate higher surface run-off, in excess of local drainage capacity, thereby causing local floods. [WMO and GWP, 2013]

Figure 1.1 illustrates how urbanization leads to a decrease of infiltration and increased surface runoff.

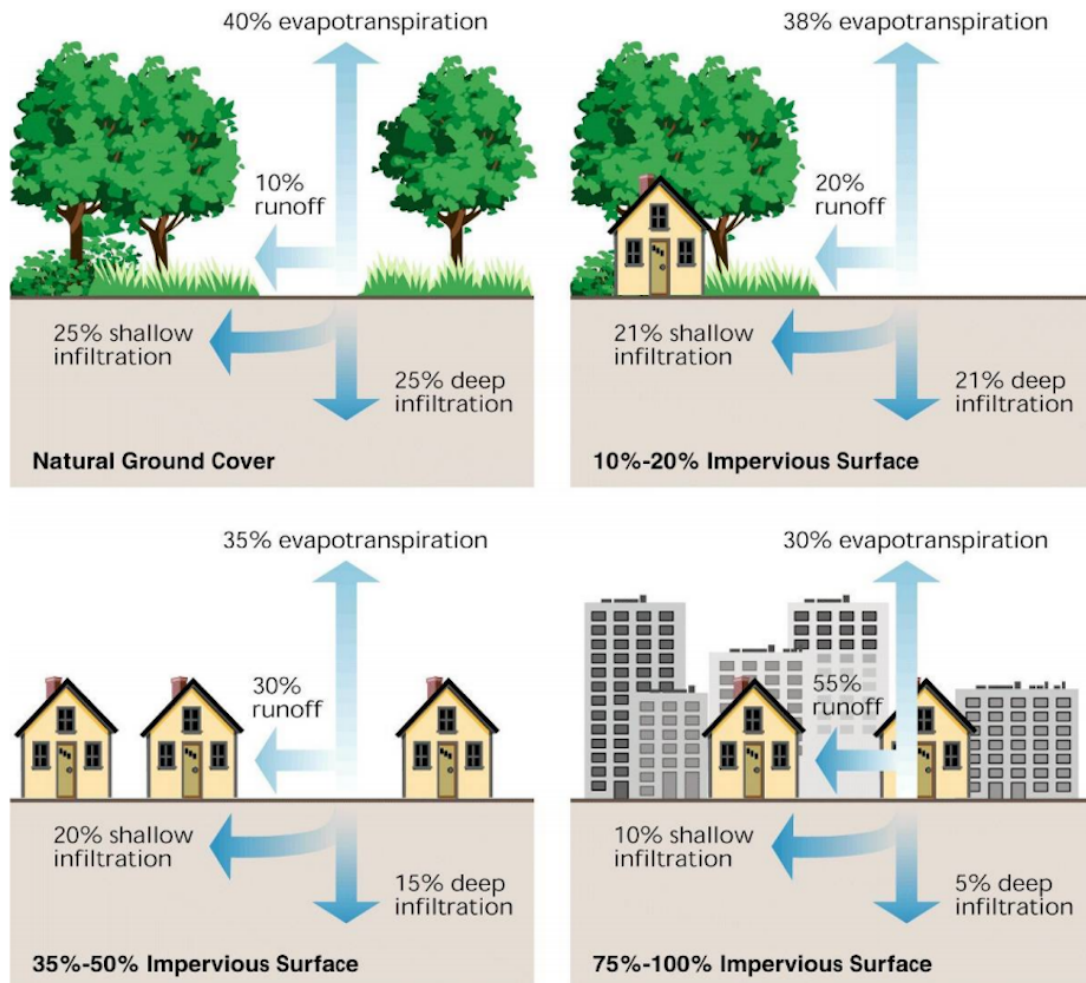


Figure 1.1. The influence of urbanization on different components of the water cycle. [USDA, 2010]

Furthermore, depending on the local hydro-geological characteristics, groundwater rising or subsurface flows can also be causes in the generation of pluvial floods. Pluvial floods are generally confined to small geographical areas and are normally not of long duration. However, in regions of lengthy rainy seasons (monsoon climates), pluvial floods can last for weeks, causing widespread damages. [WMO and GWP, 2013] An example is the UK, which in 2016 was impacted by a series of floods throughout the summer, between 15 and 17 September. This led to isolated incidents of flash flooding, impacting some communities and disrupting travel networks.



Figure. 1.2 Vehicle trapped in flood water, in Wallington, London. [Floodlist, 2016]

1.1.2 Riverine floods

River floods are triggered by heavy rainfall or snowmelt in upstream areas, or by tidal influence from the downstream. Surface conditions like soil, vegetation cover, and land use have a direct bearing on the amount of runoff produced. River floods happen when the river run-off volume exceeds local flow capacities. The river levels rise at a slow rate and the period of rise and fall is particularly long, lasting even months, particularly in areas with flat slopes and deltaic areas. In addition, the failure or bad operation of drainage or flood control works upstream can also lead to riverine flooding. [WMO and GWP, 2013]

Urban areas situated on the low-lying areas in the middle or lower reaches of rivers are specially exposed to extensive riverine floods. In most major river basins, flood plains are subjected to annual flooding. In addition, urban growth expands over some of the floodplains, decreasing the area into which floods can naturally overflow. [WMO and GWP, 2013] An example shown in the picture below happened in California where the deep floodplains of the Central Valley are subject to periodic riverine flooding.



Figure 1.3. The Eel River flooding across CA Hwy 211 [California Gov, 2016]

1.1.3 Flash floods

These are the result of the rapid accumulation and release of runoff waters from upstream mountainous areas, which can be caused by heavy rainfall, cloud bursts, landslides, the sudden break-up of an ice jam or failure of flood control works. They are characterized by a sharp rise followed by relatively rapid recession causing high flow velocities. Discharges reach a maximum quickly and diminish almost as rapidly. [WMO and GWP, 2013]

The picture below shows a flash flood in Pakistan that killed at least 53 people in 04/16.



Figure 1.4 Men collect their belongings from a makeshift shop after a flash flood caused by heavy rain on the outskirts of Peshawar, Pakistan [Newsweek, 2016]

1.1.4 Coastal floods

These types of floods are caused by high tides and storm surges caused by tropical depressions and cyclones. Coastline configurations, offshore water depth and estuary shape are factors that influence the intensity of coastal floods. Furthermore, high tides may impede the discharge of rivers and drainage systems, leading to local or riverine floods. [WMO and GWP, (2013)] Tidal effects in the estuarine reaches can make the river levels to stay high for long periods of time and sustain flooding. Thus the cities located in estuarine reaches have to bear the combined impacts of riverine as well as coastal floods due to storm surges and tidal effects. [WMO and GWP, 2013]

These types of floods happen especially in low-lying stretches of coast, for example in Southern California, as seen on the picture below that shows a levee protecting waste water ponds.



Figure 1.5 Coastal levees protecting Arcata waste water ponds from Humboldt Bay, California. Without levees protecting them, the waste water ponds flooded frequently. [California Gov, 2016]

** Impacts of urban floods*

Impacts of urban floods are considerable, especially in terms of economic losses both direct and indirect. Flood risks are a function of exposure of the people and the economic activities along with the vulnerability of social and economic fabric. [WMO and GWP, 2013] A number of urban characteristics in low and middle-income countries that have relevance to the increased flood risks are:

1. Concentrated population due to concentrated income earning opportunities;
2. Large impermeable surfaces and construction of buildings;
3. Concentration of solid and liquid waste without any formal disposal systems;
4. Obstructed drainage systems;
5. Intensive economic activities;
6. High value of infrastructure and properties;
7. Forcing out of poor from official land markets giving rise to informal settlements;
8. Housing without any health and hygiene standards; and
9. Changes in regions around cities.

1.2 Exposure.

Exposure refers to whether or not people or values are in range of floodwaters. One of the major factors for the rise in urban flood damages is the increasing number of people and assets that are physically exposed to floods in cities. The fast and unplanned growth of cities results in a larger number of people living in areas potentially liable to flooding. [WMO and GWP, 2013]. Around 2006, the global population living in cities exceeded for the first time in history the global rural population. Moreover, in developed countries, there is a preference to live close to rivers, sea and other water bodies. [WMO and GWP, 2013]. According to Anthoff et. Al, (2006), the number of people living within 1 meter of high tide level exceeds 150 million.

Furthermore, cities in many developing countries are growing rapidly. Increasing migration from rural areas to cities has led to uncontrolled urban sprawl with increasing human settlements, industrial growth and infrastructure development in hazard areas such as riversides, wetlands, land below the river, sea or reservoir level or even inside dried up river beds. [WMO and GWP, 2013]

Due to economic development, assets are growing even faster than population, and with the progress of the societies therein, the value of the assets that are now concentrated in such areas has gone unchecked and unabated. [IHDP, 2005] The human settlements and infrastructure behind such embankments assume the area to be free from flood risks, therefore ignoring the residual risks that are associated with any flood protection scheme. The infrastructure such as underground transportation systems, multi layered basements used for storage and the telecommunication networks that have indirect impacts on the economies have spiralled over the past few decades. [IHDP, 2005]

The cities and urban population, especially in developed countries, which are protected from floods with structural measures such as flood detention dams and levees have over the years intensified their economic activities in such areas. [WMO and GWP, 2013]

1.3 Vulnerability

Vulnerability is considered to be the most important component of risk because it determines whether or not exposure to a hazard constitutes a risk that may result in a disaster. If the potential exposure to floods becomes reality, then the vulnerability of

people and infrastructure is decisive for the degree of harm and damage. [WMO and GWP, 2013]

Three types of vulnerability can be distinguished:

- Physical vulnerability of people and infrastructure;
- Unfavourable organizational and economic conditions; and
- Attitudes and motivations.

1.3.1 Physical vulnerability of people and infrastructure

Urban development brings larger risks, but those in higher income groups are able to avoid or bear such risks while those with low incomes cope with them with higher difficulty. There is a socio-spatial segregation with reference to the hazard exposure of settlement locations; because, since urbanization is essentially the increase of population density, space gets rare and expensive. [WMO and GWP, 2013]

Therefore, people who cannot afford to purchase or to rent space in secure environments are forced to move to cheaper places, which may be found at the outskirts of towns. Given the fact that the livelihood of the urban poor often depends on the proximity to informal economies in the central areas of big cities, many prefer to inhabit high hazard areas inside town. [WMO and GWP, 2013]

1.3.2 Unfavourable organizational and economic conditions

The population living in informal settlements is unable to act effectively together; therefore, they face difficulties in getting support from government and make use of institutional mechanisms to the betterment of their conditions. The lack of organizational structures may lead to chaotic circumstances in times of stress, while the existence of formal or informal organizations or institutions may constitute a stabilizing factor. [WMO and GWP, 2013]

1.3.3 Attitudes and motivations

Reluctance in preparing for floods and implementing mitigation measures may be the result of lacking hazard knowledge or of fatalistic attitudes. In addition, a high dependence in external support can reduce the individual responsibility to deal with problems in a proactive manner. [WMO and GWP, 2013]

1.4 Concept of risk management.

The assessment and mapping of hazards, risks and capacities is needed in the management of the respective risks and disasters. This is depicted in the risk management cycle, which is represented with four phases as seen in figure 1.6. [International risk governance council, 2005]

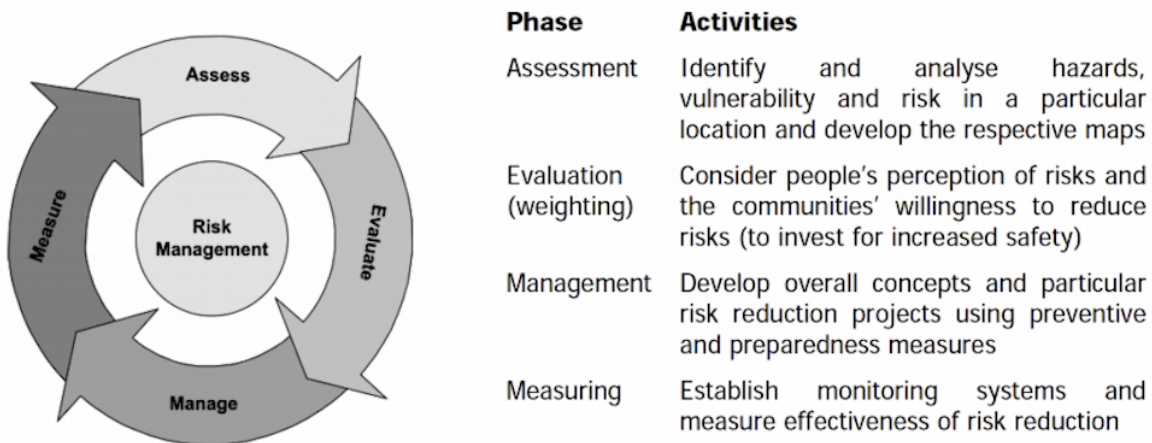


Figure 1.6 Risk management cycle. [Renn, 1992]

According to the World Meteorological Organization (WMO) and the Global Water Partnership (GWP), (2013), mapping is especially important for the assessment and management phases, in which flood maps allow the representing of flood information and management options in the geographical context. This approach is also used by FEMA in their RiskMAP programme.

In addition, flood maps play an important role in decision-making, planning and implementing of flood management options. The overall goal of flood maps is to provide information on the past and the potential extent of floods and their impacts, which is helpful when making decisions on various aspects of integrated management of floods. Moreover, developing flood maps requires a systematic process, and it is important to specify the data sets on which the maps will be based, and the methodology that will be used. Moreover, it is recommended that administrative mechanisms are implemented to develop flood-mapping programmes. [WMO and GWP, 2013]

1.5 Situation in Mexico City.

In the case of Mexico City, constant urban expansion has reduced the permeability of the soil in groundwater recharge areas. Figure 1.7 depicts the urban area as it has been expanding from 1910 to 2000 in 20-year intervals. This factor, together with land

subsidence due to over-exploitation of groundwater during the last century, has increased the risk of flooding. In fact, it is now common that floods in low-lying areas consist partially of sewage fluids.

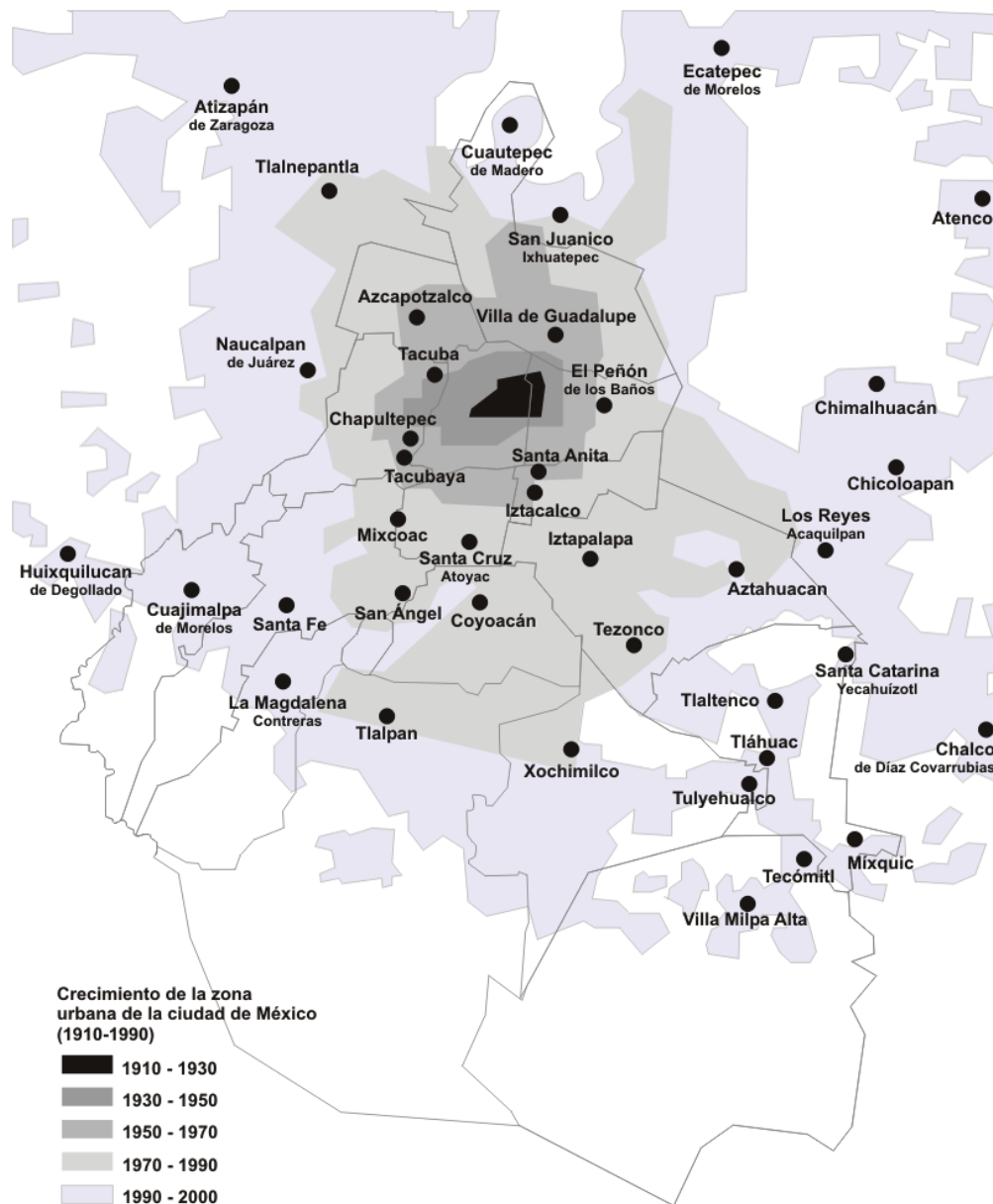


Figure 1.7 Urban expansions from 1910 to 2000 in Mexico City. [Wikimedia, 2012]

Furthermore, Mexico City urban floods are caused by the effects of deficient or improper land use planning (See figure 1.8). While there exist laws and regulations to control the construction of new infrastructure and the variety of building types, they have not been

properly enforced due to economic or political factors, or due to resource constraints. This leads to obstruction in the natural flow path of water, which causes floods. [Jha et al. 2012]



Figure 1.8 Urban expansion in the West of Mexico City due to improper land use planning. [Dailymail, 2010]

Furthermore, figure 1.9 shows the uncontrolled city growths in the Chalco area of Mexico City, a low-lying area where flooding affects the inhabitants and businesses every year.



Figure 1.9 Uncontrolled urban growths in the Mexico City outskirts. [INEGI, 2016]

According to Dominguez, (2000), the problem of flood control in the Mexico City catchment can generally be divided into local and global processes. The first are caused by rain events, which in Mexico City are typically heavy and of short duration, and the second are related to more persistent and generalized rain events, which fortunately occur less frequently, but require a solution urgently due to the high potential to cause damages. Moreover, the main factors found to cause flooding in Mexico City are:

- Development of sewer system slower than the development of the city;
- Quick growth of population causing increasing imperviousness;
- Climate change that induce shift of rainy season;
- Inadequate river regulation;
- City expansion in high-risk areas.

It should be noted that natural rivers are preserved only in mountainous areas surrounding the valley of Mexico. The rivers that cross the urban area have been cased to avoid contact of the population with sewage waters. An example is the River Mixoac, which flows naturally in the elevated areas of its sub-catchment, and continues cased

when it reaches the more a heavily populated part of the city. This can bee seen in figure 1.10



Figure 1.10 River Mixcoac flows from West to East and is encased from the point where it reaches a heavily populated area. [Google Earth, 2016]

The main contributors to the Valley of Mexico are the rivers flowing from the mountains of the West. The most important are the Magdalena, Mixcoac, Tacubaya and Hondo rivers that drain into the reservoir system that intercepts the West.

The Mixcoac, La Piedad and Consulate rivers, and in general all the primary rivers leading a path from West to East, are intercepted first by the deep drainage system and then through the Grand Drainage Canal. Discharges into the deep drain are performed by gravity and the Grand Canal by pumping. [Dominguez, 2000]

Moreover, the other major conduit to drain the discharges outside of the valley of Mexico is the Grand Drainage Channel, with the difficulty that, because of the sinking of the city, such discharges must be made by pumping.

According to Dominguez (2000), the discharge capacity of the drainage system is inadequate as some sections have worked several times per year with discharges

above capacity and have already been submitted to the black water rises and caused spilling into the streets.

The Grand Channel has been gradually reducing its discharge capacity of 90 m³ / s to 12 m³ / s in the last 30 years, and the deep drainage system is forced to drain growing areas at the South and Southeast of the city.

Moreover; according to Ibarrarán (2011), climate change will have a long term impact in Mexico City's urban infrastructure, because among urban areas, large cities, with complex urban infrastructure systems problems and ongoing environmental problems are at the mercy of these additional changes if careful planning is not done on time and proper investments put in place. Therefore, Mexico City is a relevant case study for the climate change community to understand impacts on a large, complex city. The greater metropolitan area, Mexico City Metropolitan Area (MCMA), has approximately 20 million people, over four million vehicles, very intricate systems of energy and water supply, and transportation infrastructure that may be highly vulnerable to climate change impacts. This is because it may face a range from relatively mild to extreme weather events. [Ibarrarán, 2011].

Furthermore, another critical issue is water, both at the distribution and sewage collection stages. Supplying water into the city is a great challenge because 37% comes from other basins such as Lerma and Cutzamala,. Bringing water from other basins implies driving it 127 km and elevating it up 1,100 meters, due to the altitude of Mexico City. Once it gets there, due to the outdated infrastructure and theft, 35 per cent of the water in the system is lost during distribution. [Carrabias and Landa, 2005].

In addition, due to climate change, water demand may increase and its availability may be reduced. Therefore, bringing water to Mexico City will add further pressure to its water infrastructure. The sewage system, on the other hand is quite ineffective and water treatment plants usually lack maintenance. [Ibarrarán, 2011]. Additionally there is no culture of water reuse. Moreover, rainwater and raw sewage go through the same drainage system, polluting the former and making it totally unusable for other needs. Finally, the database of water users is outdated and incomplete, so there is a limited recovery of user charges and those that pay do so at very subsidized prices. [Legorreta, 2005].

Therefore, there is a pressing need to revise the entire water system, from water capture and distribution to sewage recovery and maintenance. Operation and the scarcity cost of water should be reflected to final consumption through market pricing.

This may help to avoid over-exploitation, reduce pollution, and increase water availability for the city through the build up of water infrastructure and the implementation of water saving programs. [Ibarrarán, 2011]. Moreover, climate change tends to increase the amount of moisture retained at one moment in the atmosphere and therefore the amount of rain poured in one single episode. This leads to flooding and landslides, and as a byproduct, to soil erosion through water runoff. This additional water from floods may be thought of as an added source that could be captured through infiltration; however, given the large amount of water and the high rate at which it concentrates at one point, it usually leads to disasters, where both the government and private insurance companies have to intervene [SEMARNAP, 1997]

Precipitation in Mexico City increased from 600 mm/year in the early 20th century to over 900 towards the end of the century, as shown in Figure 1.11. Higher precipitation is associated with an increased frequency of extreme events with more than 30 mm/hr. Flashfloods have increased from 1 or 2 per year at the beginning of the 20th century to 6 or 7 towards the end. [Ibarrarán, 2011]

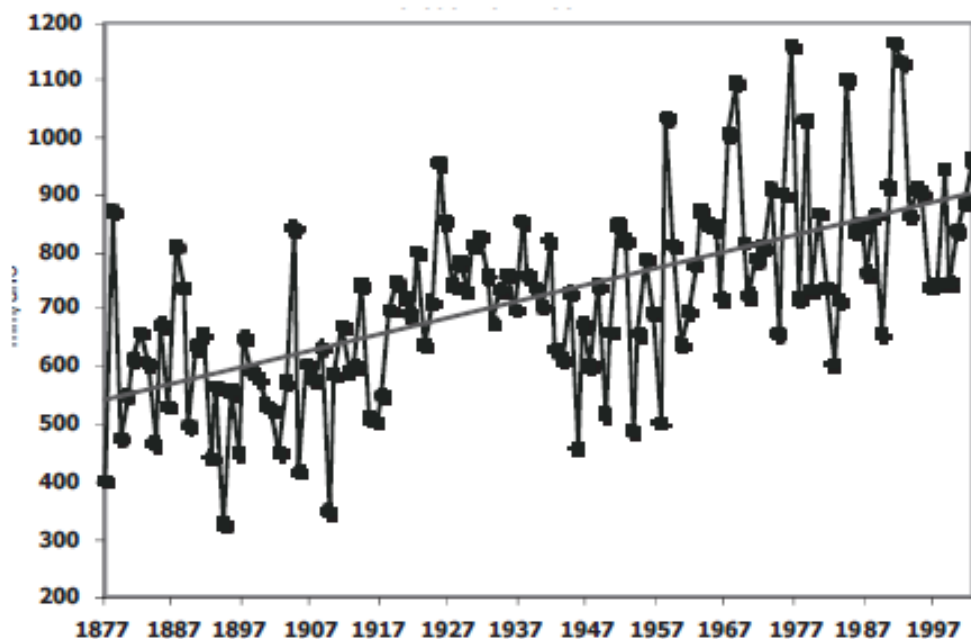


Figure 1.11 Annual rainfall in Distrito Federal, 1877-1997, (mm per year) [SMA-DF, 2006]

In addition, within the Distrito Federal alone, 24 thousand people are highly vulnerable to these water-related extreme events [SMA-DF, 2006]. Landslides happen close to the areas where water from floods typically runs through and these waterways often collect

materials and trash that increase the threat to the population and eventually block the way for water. Even though heavy rain occurs in the west of the city, floods take place in the east and south, given the way water flows and the very precarious infrastructure. Approximately 65% of these floods are due to insufficient sewage, 30% to flooding of roadways, and 5% are due to housing infrastructure. These flashfloods are expected to increase under climate change. For example, in August 2nd, 2006 there was a rainfall of 50.4 mm in only 36 minutes, causing severe floods in the south and west of the city. [SMA-DF, 2006].

In such context, it is essential for the local authorities to develop an assessment of the flood risks and then to define a global strategy for the City. However and as already mentioned, the hydrological monitoring within the Mexico basin is limited especially regarding the runoff processes.

The knowledge on the hydraulic structures implemented for collecting the runoff is also limited and no flood maps are available for the City. The challenge is then to evaluate the flood processes with an appropriate model able to produce a first assessment for every area of the Mexico basin. Obviously the task is particularly complex and request to select the most relevant modeling approach that may produce the needed results by the technicians and the decisions makers. Among many different hydrological modeling approaches, the deterministic distributed hydrological represents a potential alternative for the flood hazards analisys in Mexico City. Under physically based hypothesis, the deterministic distributed approach allows to produce, for any point within a catchment, all the hydrological characteristics including the flood hydrographs. The interest of the approach will be discussed in depth.

1.6 Hydrological models for flood inunundations assesment.

Hydrology is a subject that deals with all phases of the world's water (Chow et al., 1988). There are several components and complex interactions within the hydrological system. The hydrological system can be defined as a set of physical, chemical and/or biological processes acting upon an input variable or variables, to convert it (them) into an output variable (or variables). [Xu, 2002] This continuous converted process can be called hydrologic cycle, which is the water transfer cycle occuring continuously in nature. The three important phases of the hydrologic cycle are: Evaporation and evapotranspiration, precipitation and runoff [Raghunath, 2006]

A model is a representation of a part of the natural or human created world which can be in the form of a physical, analog or mathematical model. [Dingman, 2002]

Brooks et al., (2013) stated that Hydrologic models, simplified representations of actual hydrologic systems, predict hydrologic responses and allow one to study the function and interaction of various inputs, in order to gain a better understanding of hydrologic events. In general, a model of the hydrologic system may be explained as a function which transforms input variables into output results. [Xu, 2002] The model result can help us have a better understanding of the hydrological phenomena operating in a catchment and of how change in the catchment may affect these phenomena. Moreover, they help the hydrologist to have scientific evidences for forecasting future scenarios such as climate change or land use change, also for suggesting the constructive design in the catchment. However, a model is not able not describe all components of the hydrological system, as well as the relation between them. It only has the capacity to depict broadly this system.

Xu (2002) stated that the hydrological model is a simplified representation of a complex system which includes a number of variables such as rainfall, run-off, evapo-transpiration, temperature, infiltration, soil, moisture, etc. Therefore, this model represents an approximation of the real system. Because of the limitation in calculated capacity, the hydrological cycle of the watershed is isolated for studying in a watershed scale. This work is considered a simplification because it interrupts the spatial continuum of the hydrological system. [Xu, 2002]

A watershed can be represented with a division between topographic or groundwater as the Figure 1.12. It is defined as the terrain area contributing surface stream flow into a river network or any point of interest [Brutsaert, 2005; Chow et al., 1988; Dingman & Dingman, 1994; Linsley et al., 1949]. Therefore, speaking about a 1hydrological model, it implies that this model simulate the hydrological process for a small area or a catchment.

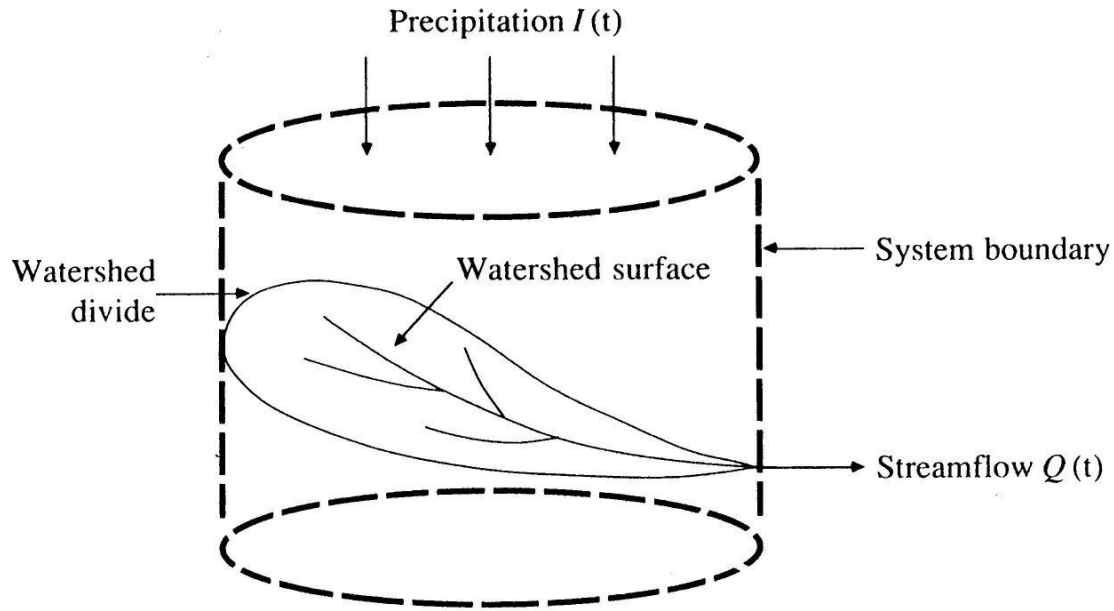


Figure 1.12 The watershed as a hydrologic system [Chow et al., 1988]

Methodologies have been proposed for inferring runoff from precipitation that is applicable to ungauged basins. These procedures are known as rainfall-runoff models. For their study they are classified according to the information they require as follows:

- * Empirical

They are of two types, one needs only the physiographic characteristics of the basin and the other, besides the characteristics, the precipitation data is used.

- * Unit hydrograph

There must be at least a simultaneous recording of rainfall and runoff to produce it.

- * Simulation of runoff from the basin

The detailed characteristics of the basin and all the simultaneous hydrological data are needed. [CNA, 2011]

1.6.1 Model selection criteria.

The criteria for selecting a hydrological model depends on several factors. These criteria usually change due to the purpose of study, such as planning or operation, which basically require different kinds of hydrological models [Plate, 2009]. They also depend on the real conditions of the catchment, and data availability [Ng & Marsalek, 1992]. However, these criteria concentrate generally on four fundamental requirements:

- Required model outputs to be estimated by the model;
- Hydrologic process that needs to be modeled in order to estimate the desired outputs adequately;
- Availability of input model;
- Cost. [Cunderlik, 2003]

For every study, the first requirement for choosing a hydrological model is to define how to describe accurately the processes of catchment in certain conditions. For this purpose, an insight was proposed that the more detailed the characteristics of catchment the model are, the more detailed and potentially more correct descriptions of the hydrological process the model will represent. [Refsgaard, 1997; Vansteenkiste et al., 2013]. As such, this could reduce the uncertainty of the model when simulating the hydrological events and forecasting for the future. Cunderlik, (2003) proposed that the selected model must have the capacity to answer the following requirements:

The selected model should supply:

- Simulated low peaks (stage, discharge), volumes and hydrographs at outlets of sub basins, and in the profiles of points of interest within the main basin;
- Simulated long flow sequences for water budget and drought analyses primarily for the main basin and preferably for the individual sub basin;
- Simulated extend of flooded area for different precipitation events and various basin conditions.

The main hydrologic processes that need to be included in the structure of the hydrologic model in order to adequately estimate the required project's output are:

- Single-event precipitation runoff transformation based on various antecedent basin conditions and spatial and temporal precipitation distribution;
- Continuous precipitation runoff transformation based on various antecedent basin conditions and temporal precipitation distribution;
- Snow accumulation and melt;
- Interception and infiltration, soil moisture accounting;
- Evapo- transpiration;
- Regulated reservoir operation. [Cunderlik, 2003]

Furthermore, in large catchments where the hydrological components are in interactive relations, the understanding of the hydrological mechanics in large scale is intricate and complex. This leads to the modeler not being able to define which one is the main factor

affecting the stream flow. Therefore, for these cases, using a distributed model is required to simulate the rainfall runoff behavior [Wittwer, 2013]. According to the World meteorological organization (WMO), a distributed hydrological model is expected to describe more accurately than others where the topography varies greatly. This insight might rely on the grid scale of the distributed model. Moreover, this kind of model will represent more accurately the slope variation. The Table 1.2 indicate the standards which WMO recommend to choose a model for simulating the hydrological cycle in a catchment [Wittwer, 2013]. This criteria was taken into account and compared with the catchment conditions to select the most suitable model for simulating the hydrological process of the Mexico City catchment.

Model type	Question 1	Catchment size?		
		Small (headwater)	medium	large
	Catchment model	lumped	semi distributed	distributed
	Routing	mostly not needed	hydraulic/hydrology	hydraulic, hydrology, gauge to gauge correlation
	Question 2	Catchment relief?		
		Flat/plain	Moderate/hilly	Pronounced/ Mountainous
Model features	Catchment model	lumped	semi distributed	distributed
	Question 3	Does soil wetness effect flood generation?		
		no	to some extent	yes
	Soil water budget feature required	not need	recommended	need
	Question 4	Is snowmelt important for flood generation?		
		no	to some extent	yes
	Snow module	not need	recommended	need
	Question 5	Is river regulation (reservoir/lake/ diversions) affecting floods?		
		no	to some extent	yes
	Storage module	not need	recommended	need

Table 1.2a Standard for model selection proposed by the WMO [Wittwer, 2013]

Data requirements	Question 6	What is the predominant flood causing rainfall?		
		Seasonal	frontal/ advective	convective
	Recommended data resolution	daily	daily/hourly	hourly/ sud-hour
	Question 7	What is the required leadtime?		
		Short	Medium	Long
Constraints	Required rainfall data	Observed rainfall	Rainfall nowcast is recommended (e.g radar)	rainfall nowcast and/or forecast from NWP's is required
	Question 8	Is distributed/ gridded data available?		
		no	yes	
		Lumped model is only option	semi-distributed/ distributed model is feasible	
	Question 9	What is the level of capacity of the service?		
		low	intermediate	high
		only simple toll feasible (correlation, etc)	run lumped/ black box simple model	all option available

Table 1.2b Standard for model selection proposed by WMO [Wittwer, 2013]

1.6.2 MIKE SHE Model.

According to the criteria discussed in section 1.6 a higher performance of the distributed physically-based hydrological model over other kinds of models in hydrological simulations can be expected. The structure of a fully distributed physically-based hydrological model is a combination of the distributed characteristics and physical interpretation of the hydrological process, hence it is expected to provide significant advantages over existing hydrological models for a wide range of applications. This kind of model has the ability to simulate almost all components of the hydrological process. Furthermore, this process is solved at the grid scale, thus it helps to overcome the data problem in a large catchment, and in catchments with limited data, as is the case of

Mexico City catchment. This advantage is highlighted as one of the most important aspects of the physically-based distributed model. Therefore, the main attribute of a fully distributed physically-based hydrological model is that it is able to provide hydrological information at any location within the catchment. The catchment characteristics are able to be input into the model as detailed as possible, and also, it helps to reflect the catchment nature truthfully, thus reducing the uncertainty in simulation and increasing confidence in simulation. This also allows to investigate in depth the hydrological dynamics of catchment. In addition, the model calibration can be ignored because of describing in reality the physical hydrological components and because this model is able to represent the catchment with the simplest set-up, in comparison with any other models [Abbott et al., 1986]. Several modeling tools are available today and could be used for such analysis. One of this kind of models is MIKE SHE, developed by DHI Water & Environment.

MIKE SHE was developed with the aims of providing scientific information for optimizing the water resource project planning, also for estimating the impact of urbanization, land use change, infrastructural development on the hydrological process and on water resource development and management in Europe in the 70s. A new generation of hydrological model, which focused on the physically based distributed catchment model, was required. The model was hoped to have the potential to overcome many of the deficiencies related with simpler approaches. The European Hydrological System-Système Hydrologique Européen or SHE was born from this situation to answer this requirement. After having the success in modelling the hydrological phenomenon in Europe, SHE has become the starting point for many physically based spatially distributed hydrological models, such as SHETRAN, SHESED, MIKE SHE [Ewen et al., 2000]. SHE was a result of the cooperation between three european establishments in water modelling including the British Institute of Hydrology, UK, The Danish Hydraulic Institute and the French Consulting Company SOGREAH under the financial support of European Commission [Abbott et al., 1986].

The SHE model was built fundamentally on the blueprint proposed by Freeze and Harlan in 1969 for modelling the hydrological cycle [Abbott et al., 1986]. According to the blueprint theory, the run off process is divided in different parts and solved by corresponding equations. Using different equations focused on representing more accurately the physical characteristics of each part in the catchment [Freeze & Harlan, 1969]. The algorithm was developed independently in three organizations under the form of software module, the Institute of Hydrology, UK; is responsible for snowmelt,

interception and evapotranspiration; overland flow and channel flow is constructed by SOGREAH and the Danish Hydraulic Institute is in charge of the flow components in unsaturated and saturated zones, and for linking the module together [Abbott et al., 1986].

After tests to validate the quality of the model with several case studies, the first version of SHE became operational in 1982. From that time, the SHE model has seen a continued completion and upgrading by DHI Water & Environment with a new name: MIKE SHE. This model kept developing to improve the quality of simulation. Today, MIKE SHE is considered a high performance model for hydrological modelling. It includes a full suite of pre and post-processing tools, plus a flexible mix of advanced and simple solution techniques for each of the hydrologic processes. MIKE SHE covers the major processes in the hydrologic cycle and includes process models for evapotranspiration, overland flow, unsaturated flow, groundwater flow, and channel flow and their interactions. Each of these processes can be represented at different levels of spatial distribution and complexity, according to the goals of the modeling study, the availability of field data and the modeler's choices, [Butts et al., 2004; Graham & Butts, 2005]. The MIKE SHE user interface allows the user to intuitively build the model description based on the user's conceptual model of the watershed. The model data is specified in a variety of formats independent of the model domain and grid, including native GIS formats. At run time, the spatial data is mapped onto the numerical grid, which makes it easy to change the spatial discretization [Graham & Butts, 2005a].

Furthermore, MIKE SHE uses MIKE 11 to simulate channel flow. The MIKE SHE/MIKE 11 coupling allows to simulate large water bodies such as lakes and reservoirs, as well as flooded areas. If this option is used, MIKE SHE/MIKE 11 applies a simple flood-mapping procedure where MIKE SHE grid points, are linked to the nearest H-point in MIKE 11. Surface water stages are then calculated in MIKE SHE by comparing the water levels in the H-points with the surface topographic elevations. Conceptually, the flooded cells are "side storages", where MIKE 11 continues to route water downstream as 1D flow, and at the same time, the water is available to the rest of MIKE SHE for evaporation and infiltration. The effect of urban drainage and sewer systems on the surface/subsurface hydrology can be simulated in the MIKE SHE model via the coupling with the MOUSE model and nowadays it develops a couple of MIKE URBAN and MIKE SHE [DHI, 2012f].

1.6.3 MIKE SHE architecture.

The preeminence of the deterministic, physics-based, distributed model code in the hydrological domain has been demonstrated. These advantages have been concretized in the MIKE SHE model. However, beside the capacity to translate accurately the hydrological process for a catchment, the applicability of deterministic physics-based distributed model in reality confronts several difficulties. The requiring of a significant amount of data or long execution time are the most important limitations when applying the physical based model. In addition, there is the question: is it really necessary to simulate all hydrological components in one model? How will it improve the simulation quality when just one or two hydrological processes dominate the watershed behavior [Graham & Butts, 2005]. These two authors give a judgment that a complete physics based flow description for all process in one model is rarely necessary. Over-parameterized description may occur for simple applications; therefore, MIKE SHE has been developed with many simulated methods, such as lumped and conceptual. This integration is organized in a modular approach which includes several solution techniques to translate the different processes in nature. It can help to optimize the function of each component when simulating for a complex catchment. Each of the hydrological processes can be represented at different levels of spatial distribution and complexity, according to the goals of the modelling study, the availability of field data and the modeller's choices [Butts et al., 2004]. Figure 1.13 presents a schematic overview of the processes in the MIKE SHE model. According to this, the hydrological process is divided into eight parts in the MIKE SHE model. The description of these parts is briefed as follows.

a. Precipitation.

Precipitation is a key factor in the hydrologic process; it is always the first data requirement with any rainfall run-off model. This input data affects considerably on the simulation quality. In MIKE SHE, precipitation data can be input as a constant value or a time series.

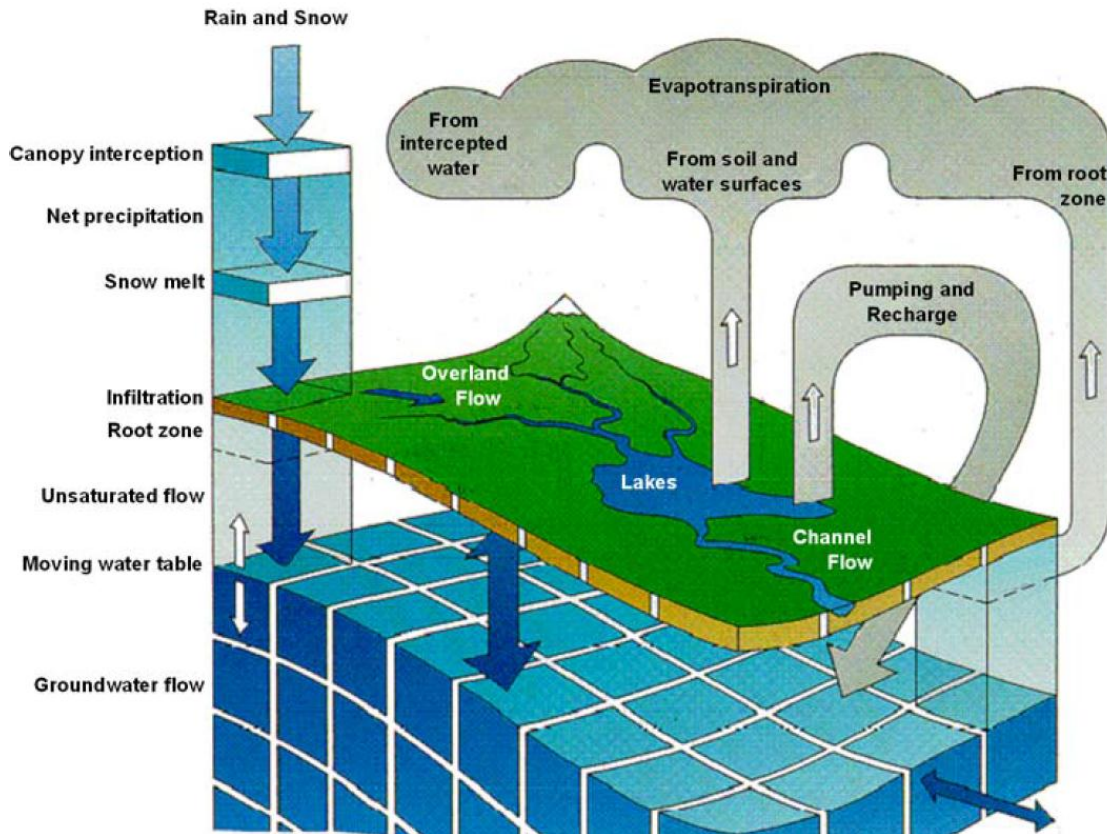


Figure 1.13 Schematic of MIKE SHE model [DHI, 2012e].

MIKE SHE supplies three spatial distributed formats for rainfall input, such as uniform, station based or full gridded spatial distribution. The first format generally is applied for a small catchment or a lack of surveyed data. The second one is suitable with locality where the density of gauging station is relatively high. The most widely used of this type is Thiessen Polygons. The latter one is the best in representing the precipitation data and is expected to improve the simulated quality. However, this data is difficult to obtain because precipitation is typically measured at only a few locations within a watershed. In fact, this data is not always available. It is generally obtained via several interpolated methods. MIKE SHE also provides a tool to correct the rainfall variation due to the elevation via Precipitation Lapse Rate. Snow melt is an important phenomena that can dramatically affect the spring runoff timing and volume. Therefore, a realistic description of the snow melt process is important. [DHI, 2012e].

In order to take into account the impact of snow in the stream river, MIKE SHE includes a comprehensive snow melt module based on a modified degree-day method. Precipitation that occurs when the air temperature is below the freezing point accumulates as solid snow and does not infiltrate or contribute to runoff. The

accumulated snow has a moisture content, and when the moisture content reaches a critical level, then additional melting contributes to runoff. [DHI, 2012e].

b. Evapotranspiration

In the water balance, the evapotranspiration is an important component. This factor is composed from evaporation and transpiration. Evaporation, in which water changes from a liquid to gas or vapor. In hydrology, it is estimated as the primary pathway to which water moves from the liquid state back into the water cycle as atmospheric water vapor. It occurs from free water surface including lakes, rivers, snow surface or from the soil. The evaporated amount might be affected by many factors such as temperature, humidity, wind, soil wetness, soil hydraulic properties and the groundwater table. In a different way, the transpiration is defined by plant physiology - the depth of the roots, the ability of the roots to extract water from the soil or characteristics of leaves [Graham & Butts, 2005^a]. In MIKE SHE, the calculation of evapotranspiration uses meteorological and vegetative data to predict the total evapotranspiration and net rainfall due to the following components: interception of rainfall by the canopy, drainage from the canopy to the soil surface, evaporation from the canopy surface, evaporation from the soil surface, and uptake of water by plant roots and its transpiration, based on soil moisture in the unsaturated root zone [DHI, 2012e].

MIKE SHE 2012 supplies three methods to determine the amount of actual evapotranspiration (ET):

- Soil Vegetation Atmosphere Transfer (SVAT)

This model was developed based on a system that consists of two layer (soil and canopy) and their resistance network link [Shuttleworth & Wallace, 1985]. This model includes a single, semi-transparent canopy layer located above the soil layer. In this model, actual evapotranspiration is calculated directly from standard meteorological and vegetation data. This process is not dependent on Reference evapotranspiration [Graham & Butts, 2005^a].

- Kristensen and Jensen Method.

In this method, the actual ET is estimated by using empirically derived equations [Kristensen & Jensen, 1975]. This equation was established at the Royal Veterinary and Agricultural University in Denmark. The equation is a result of summarizing the field measurements. The model solves the relationship between the reference evapotranspiration rates, maximum root depth and leaf index of the plants to give the

actual evapotranspiration and the actual soil moisture status. The precipitation is assumed to not occur as snow because the considered temperature of model is above 0°C. The required data for this method are time series of the Reference ET, the leaf area index and the root depth, and other empirical parameters that control the distribution of ET with the system [Graham & Butts, 2005a].

The mechanism of this method can be expressed as follows: first, the water intercepted by the leaves is removed from total rainfall. This number will drop into ground surface where it can infiltrate or pond. Based on the ponded at reference ET and the net rainfall, the model will calculate the evapotranspiration. If the amount of evapotranspiration is still smaller than Reference ET at current time step, the water loss will continue to be subtracted by transpiration. The ET distribution between unsaturated zone and saturated zone relies on the root's depth. The evapotranspiration is extracted from saturated zone only when the roots of vegetation are in contact with the water table [DHI, 2012e]. This is very important to calculate the evapotranspiration at swamps, wetlands, and the flood season. The Kristensen and Jensen Method is required when using the Richards equation and gravity flow methods in the unsaturated zone [Graham & Butts, 2005a].

- Two Layer Water Balance Method.

It aims at reducing the complexity of simulating the transpiration process at water flow at the unsaturated zone. MIKE SHE proposes a simplified water balance method. This method is the Two Water Balance Model which divides the unsaturated zone in two parts. The first is root zone where evapotranspiration mostly occurs. The second part is below the root zone, that does not affect much on the evapotranspiration process. This model is constructed based on the research of Yan & Smith (1994). The main objective of this model is to calculate the actual evapotranspiration and solve the relation between surface and ground water. The simulation process in the Two Water Balance Method progresses as the Kristensen and Jensen Method. Following that, the evapotranspiration is determined via the processes of intercepted water, then ponded water and finally transpiration from root zone. However, it does not take into account flow dynamics which is a difference with the Kristensen and Jensen Method. The data requirement of this model is the time series for root depth, leaf area index and Reference Evapotranspiration [Graham & Butts, 2005a]

This method is particularly suitable in swamps or wetlands where the ground water table is shallow. In these cases, the actual evapotranspiration rate is close to the reference

rate. In areas with a deeper and drier unsaturated zone, the Two Layers Water Balance Method is inefficient. However, the model result can be acceptable via calibration [Graham & Butts, 2005a].

c. Unsaturated Flow

In the unsaturated zone, the flow can be expressed in vertical and horizontal directions. However, under the domination of gravity, the vertical has main ammounts. Therefore, MIKE SHE assumes that there is only vertical flow in the unsaturated zone and it ignores the lateral movement (Figure 1.14). This assumption is applicable for most situations. However, it may limit the validity of the flow direction in several cases, such as on very steep hill slopes or in small scale models with lateral flow in the unsaturated zone where the intensity of lateral and vertical flow is roughly similar. The rainfall fulfill the soil moisture and the water in this part will be extracted for evapotranspiration and recharge to the groundwater table. [Graham & Butts, 2005a]

Depending on deferent tools, the UZ flow component is able to simulate with four options as follows:

- Richards Equation:

The full Richards equation (equation 1) is developed based on the continuity equation and Darcy's law. The method uses the vertical gradient of hydraulic head, which includes both a gravity and a pressure component, to represent the water movement in the unsaturated zone. The pressure head as a function of saturation (moisture retention curve) and hydraulic conductivity are necessary for this method. The evapotranspiration factor is calculated as a root extraction in the upper part of the unsaturated zone. The amount of total actual evapotranspiration is equal to the integral of the root extraction over the entire root zone depth.

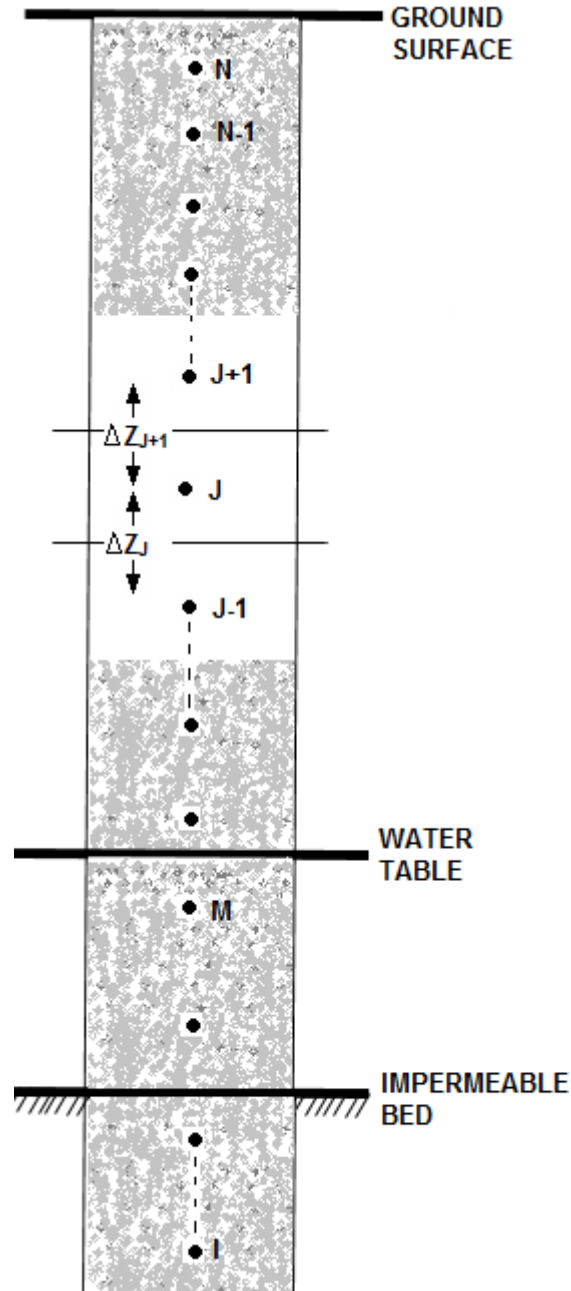


Figure 1.14 Vertical discretization in unsaturated zone. [DHI, 2012e]

Direct evaporation from the soil is considered only for the first node below the ground surface.

$$C \frac{\partial \psi}{\partial t} = \frac{\partial}{\partial z} \left(k(\theta) \frac{\partial \psi}{\partial z} \right) + \frac{\partial K(\theta)}{\partial z} - S \quad \text{Eq. 1}$$

Where Ψ is pressure head,

θ is the volumetric soil moisture

$K(\theta)$ is the unsaturated hydraulic conductivity

Z is the gravitational component

S is the root extraction sink term

T is the time component

C is the soil water capacity

This method is accurate for describing the flow in the unsaturated zone. However, it is limited in computational time due to its complexity. [Graham & Butts, 2005a]

- Gravity Flow

The limitation about the computational time of the Richards equation method is improved with the Gravity Flow method. By assumption that the gravity is the main role in vertical driving force, Gravity Flow ignores the effect of the pressure head term on vertical flow in the unsaturated zone.

$$\frac{\partial \theta}{\partial t} = -\frac{\partial q}{\partial z} - S(z) \quad \text{Eq.2}$$

Where θ is the volumetric soil moisture

$K(\theta)$ is the unsaturated hydraulic conductivity

Z is the gravitational component

S is the root extraction sink term

T is the time component

In the Gravity Flow Module, equation 2 is solved explicitly from the top of the soil column downward. At the top of the soil column, the depth of overland water in the ground surface is hypothesized as the amount of water available for infiltration, which is used as infiltration rate in the first step and as the maximum infiltration rate for the soil column. The data requirement of this method is only the conductivity –saturation relationship.

In comparison with the full Richards equation, this simplified method is faster and more computationally stable. This is applicable for coarse soils which capillary pressure is quite small and for projects focused on the accuracy of evapotranspiration, of recharge to groundwater, but not on the dynamics in the unsaturated zone.

Two-Layer Water Balance

The two layer water balance method divide the unsaturated zone in two parts, the root zone and below. This assumes the unsaturated zone storage is inconsiderable. Thus two layer water balance method does not take into account this component in infiltration and it supposes all infiltrated flow recharge immediately to the saturated zone. The simple of this engine helps to reduce lot of simulation time at least with the long simulation. This method is particularly suitable with swamps or wetlands area where the ground water table is shallow.

- **Lumped Unsaturated Zone Calculation (Column Classification)**

Lumped Unsaturated Zone Calculation is applicable in the case of identical unsaturated flow conditions. The unsaturated flow conditions in two cells is considered as identical if they answer completely two following conditions:

- The first is identical soil and vegetation characteristics.
- And the second is boundary conditions. In this context the flow in

the unsaturated zone can be calculated in one of the cells which is as a representative of a group. Then other cells can refer on the result of this cell. This method gives approximated accurate results for water balance simulations. It is not accurate for local dynamics, because it does not account the influence of this procedure on the flow simulation.

In summary, DHI (2012e) stated that the full Richards equation method is the most computationally intensive but also the most accurate when the unsaturated flow is dynamic. The simplified gravity flow procedure provides a suitable solution when the primary interest is in the time varying recharge to the groundwater table based on actual precipitation and evapotranspiration and not dynamic in the unsaturated zone. The two simple layer water balance method is suitable when the water table is shallow and groundwater recharge is primarily influenced by evapotranspiration in the root zone. Lastly, the Lumped Unsaturated Zone Calculation is suitable with long times of simulation at homogeneous zones.

Moreover, MIKE SHE also describes the flow through macropores in unsaturated soil which is important for many soil types. There are two selections for representing flow type in MIKE SHE, Simple bypass flow and full macropore flow.

Simple bypass flow is a simple empirical function used to describe simple bypass flow in macropores. The infiltration water is divided into one part that flows through the soil matrix and another part, which is routed directly to the groundwater table, as bypass

flow. The bypass flow is calculated as a fraction of the net rainfall for each UZ time step. The actual bypass fraction is a function of a user-specified maximum fraction and the actual water content of the unsaturated zone, assuming that macropore flow occurs primarily in wet conditions [DHI, 2012e].

In the Full Macropore Flow, macropores are defined as a secondary, additional continuous pore domain in the unsaturated zone, and the matrix pore domain representing the microporous bulk soil. Macropore flow is initiated when the capillary head in the micropore domain is higher than a threshold matrix pressure head, corresponding to the minimum pore size that is considered as belonging to the macropore domain. Water flow in the macropores is assumed to be laminar and not influenced by capillarity, thus corresponding to gravitational flow [DHI, 2012e].

In order to overcome the capacity of 2-Layer WB and the Gravity Flow UZ solution methods about the capillarity simulation, DHI provides the The Green and Ampt infiltration function which is an analytical solution to the increased infiltration experienced in dry soils due to capillarity.

The coupling the unsaturated zone to saturated zone is solved by an iterative mass balance procedure. This linking ensures a realistic description of water table fluctuations in situation with shallow soils. However, there is a difficulty in solving the linkage between the two saturated and unsaturated zone which are arisen from the fact that these two components are explicit coupled and run in parallel. This couple is not solved by a single matrix with an implicit flux coupling of the unsaturated zone and saturated zone differential equations. A great advantage of this kind of coupling is that, they are run with different time steps.

d. Overland Flow

The surface run off can be caused from ponded water which has the tendency to flow downhill towards the river system. The ponded water can be from the remaining rainfall water after the losses of infiltration and evapotranspiration, from river flow flood over the banks or groundwater flows onto the surface. The characteristics and quantity of this hydrological components are defined by the topography and flow resistance as well as the losses due to evapotranspiration and infiltration along the flow path. MIKE SHE provides two methods for representing this main component of hydrology.

- Finite differences Method.

MIKE SHE handles the St. Venant equations to solve the run off in the ground surface. However, this equation is simplified by ignoring momentum losses due to local and convective acceleration and lateral inflows perpendicular to flow direction. After simplifying, it becomes the diffusive wave approximation. This method is suitable when simulating the free surface flow, the shallow water depth or slow velocity of surface water. The diffusive wave approximation is solved by using the two dimensions difference approach to represent the relationship between the rainfall, evapotranspiration, infiltration and the surface flow. For this method, it is necessary to supply into the model three parameters:

- The Manning number which describes the friction of ground surface,
- The detention storage. The parameter to limit the amount of water that can flow over the ground surface. It means that the overland flow process only occurs if the ponded water on the surface exceed this threshold. The detention storage is accounted for infiltration or evapotranspiration. This parameter also affects the exchange between overland flow and channel flow.
- Initial water depth: In most cases it is the best to start a simulation with a dry surface and let the depressions fill up during a run in period. However, if there are significant wetlands or lakes this may not be feasible. So this parameter is needed for the model to reach quickly a balance condition.

An empirical relation between flow depth and surface detention, together with the Manning equation describing the discharge under turbulent flow conditions is handled in MIKE SHE to describe the overland flow [Crawford & Linsley, 1966]. This method is known as Semi-distributed Overland flow and is applied in many hydrological models such as SWM, HSPF or WATBAL.

e. Channel Flow

In theory, the MIKE SHE model has the ability to simulate accurately the stream and river flow as a two dimension surface flow if the topography data is fine enough. However, this requirement is difficult to achieve. The high resolution topography data is an obstacle for applying this method. In general, this data is not available at least in large catchments. Even If this data is available, the second problem is the computation issue. In this kind of simulation, it is necessary to have a strong computer system and a longer simulation. In order to overcome this issue, the river flow is assumed as one dimension flow. This component is simulated by a coupling with River hydraulic program MIKE 11 which was professionally developed based on an implicit, finite difference

scheme for the computation of unsteady flows in rivers and estuaries. Moreover, the coupling between 1D and 2D models helps the MIKE SHE model simulate a wide range of hydraulic control structures, such as weirs, gates and culverts, for which the algorithm of MIKE SHE has been not developed yet.

1.6.4 MIKE SHE performance in past studies.

MIKE SHE is used in a broad range of applications in a high number of countries around the world by organizations ranging from universities and research centers to consulting engineers companies [Refsgaard et al., 1995]. MIKE SHE has been used for the analysis, planning and management of a wide range of water resources and environmental and ecological problems related to surface water and groundwater, such as: River basin management and planning, water supply design, management and optimization, irrigation and drainage, soil and water management, groundwater management, interaction between water surface and ground water, ecological evaluations flood plain studies and impact of land use and climate change.

Following, several examples are provided about the flexibility of MIKE SHE in hydrological modeling. This part includes the applied topography, catchment modeling scale and simulated objective.

a. Morphological diversity

Throughout its history, the MIKE SHE model has validated its suitability with many topographical types. Andersen et al., (2001); Graham, & Butts (2005) applied the MIKE SHE model to simulate the hydrological process of Senegal River Basin. This model was developed including all of the hydrologic components. The result was preventative of the characteristics of this catchment with acceptable statistical coefficients. Thompson et al., (2004) used this model to simulate the hydrological system in a lowland wet grassland in southeast England. These authors used MIKE SHE coupling with MIKE 11 to represent the hydrologic factors in Elmley Marshes catchment. This research gave remarkable results in simulating surface flooding, groundwater and flow in the channel. The application of the coupled MIKE SHE/MIKE 11 modelling system to the Elmley Marshes has demonstrated its potential to represent complex hydrological systems found within many wetland environments. By simulating the stream flow process at a catchment in China, and in Hawaii, U.S.A., the study of Sahoo et al., (2006) and Zhang et al., (2008) showed the capacity of MIKE SHE to describe the flow in mountainous regions.

This model has also been preeminent to simulate hydrology in semi-arid areas with the studies of McMichael et al. (2006). These demonstrations prove that MIKE SHE have a strong ability for describing catchment hydrologic characteristics. This capacity is suitable for any topography, from lowland to mountainous or semi-arid areas.

b. Catchment modeling scale

Operating on a flexible mechanism, the size of cell in MIKE SHE can be changed flexibly to adapt with real situations. Thus, the algorithm does not limit the modeling scale of the study area. It leads to the advantage of using this model in watershed hydrological simulations. Indeed, the MIKE SHE model has operated well in a wide range of scales. This was illustrated throughout the research of Sahoo et al., (2006), Zhang et al., (2008).

c. Simulated objective:

The MIKE SHE model has been used for:

- Hydrological process. MIKE SHE model with its advantage in taking into account most of the components in catchment's hydrology has been handled successfully to represent hydrological process for many locations all over the world. Especially, it can be used for special objectives such as snowmelt or flood simulation. Ma et al., (2013) accounted the snowmelt component in the run off of 19,000 km² mountain area at Northwest China. Integrating as much as possible the hydrological components into the model is necessary for assessing the snowmelt flow. These authors said that after using MIKE SHE, extreme snowmelt floods of Seim River physiographic zone of the European Russia, was represented accurately in the environment of MIKE SHE. This study was realized by study of Gelfan (2010).
- Flood analysis: MIKE SHE calculates the overland flow cell by cell and can link with 1D model, hence this distributed model is expected to present accurately the flood event. Furthermore, the model can give the result as 2D data, so it helps this model has the advantage in mapping the flood area. In effect, this model has already proved its remarkable characteristic in many studies. Sen & Niedzielski, (2010) applied MIKE SHE for evaluating the flood phenomenon at the second largest river of Poland. Nielsen (2006), utilized the MIKE SHE for floodplain inundation and urban drainage assessment in South East Asia.
- Impact of land use changes: The MIKE SHE model have been also used for evaluating the impact of land use change to the catchment's hydrology.

Oogathoo, (2006) after comparing with others models, selected MIKE SHE to evaluate the impact of management scenarios on the hydrological processes of the watershed by applying land-use increase/decrease percentages over Canagagigue Creek catchment, Ontario, Canada. Consequently, the study show that this model performed well in simulating runoff. The capacity of MIKE SHE model in investigating the relation between land use change and hydrological process was confirmed in a study by Wijesekara et al., (2014). It was realized to assess the consequence of land use change over 1,238 km² of Elbow River, southern Alberta, Canada [Wijesekara et al., 2014]. This study demonstrated the performance of MIKE SHE in presenting the impact of land use change on the hydrological process. Through the result, the authors confirmed the advantage of this deterministic distributed model.

- Ecosystem and water quality: The Diversity of the MIKE SHE application has been also expressed via its ability in the impact of ecosystem on catchment's hydrology. One evidence of this approach was showed in its application at Ecosystem Based Water Resources Management to Minimize Environmental Impacts from Agriculture Using State of the Art Modeling Tools in Strymonas Basin. This project used MIKE SHE to estimate to the impact of ecosystem to Strymonas Basin, in the south of Europe [Doulgeris et al., 2012; Halkidis & Papadimos, 2007]. The study over 16,747 km² of this Balkan basin proved the flexibility of MIKE SHE model in representing the hydrological process.
- Groundwater analysis: By accounting most hydrological components and especially possessing a correct algorithm for ground water modelling, this model has been highlighted when simulating the ground water. In reality, many authors have been using MIKE SHE model for ground water studies. Demetriou & Punthakey,(1998) used MIKE SHE to evaluate the groundwater management options for dealing with rising water table levels and land salinization problems in an Australian watershed. Based on the modelling results they commented that MIKE SHE is well suited to describe the dynamic interaction between the surface and subsurface water systems. The efficiency of this distributed hydrological model for ground water modeling was also confirmed by the study of Liu et al., (2007). By testing the relation between surface and ground water over 91.76 km² of the Tarim basin in China, these authors indicated clearly the usefulness of MIKE SHE model for ground water modelling. Their successful application with MIKE SHE described an efficient method for analyzing groundwater dynamics

and their response relationship to environmental factors. Moreover, certain studies also applied MIKE SHE to investigate ground water components in a catchment scale [Jourde et al., 2007; Sonnenborg et al., 2003]. This model benefited the assessment of the exploitable groundwater resources of Denmark. By simulating the different scenarios on MIKE SHE, Henriksen et al., (2008) proposed a complete ground water resource map over Denmark. The study also outlined the exploitable capacity for each region of this country. Furthermore, the model has as well been used for calculating discussion of argents in ground water environment, such as the research of Thorsen et al., (2001). In this study, MIKE SHE was used as a basic tool for simulating the nitrate leaching to the aquifer at catchment scale in Karup catchment, Denmark.

- Irrigation strategy: Starting from land use distribution and vegetation functions which can introduce most of the characteristics of vegetation due to their growth process, this distributed model has been used for simulating the water demand of each plant. Based on these demand, water requirements for irrigation are easily calculated. In fact, the function of MIKE SHE has already been handled to determine the need of water in agricultural zones. Jayatilaka et al., (1998), and Singh et al., (1999) were based on MIKE SHE results to design the irrigation plan for a tropical sub-humid area in India. The authors concluded that MIKE SHE is primarily proposed here as a planning tool and not as a real-time scheduling tool in irrigation planning.
- Evapotranspiration analysis. There have been several authors that used MIKE SHE to simulate this process in hydrological cycle. Vázquez & Feyen, (2003) evaluated the effect of potential evapotranspiration to the hydrological cycle at a medium-size catchment. Moreover, Vu et al., (2008) used MIKE SHE for determining these components over a large catchment in central Vietnam.
- Climate change impact assessment. Global warming is expected to affect mostly to catchment's hydrological factors, for example precipitation, evapotranspiration, ground water, ecosystem, etc. Hence, simulating the impact of this phenomena towards the stream flow requires a model which can represent the hydrological components of catchments as much as possible. Bosson et al., (2012) applied MIKE SHE model for simulating the terrestrial hydrology associated with different climate over 180 km² of Forsmark Catchment, Sweden. In this study, the change in future temperature, rainfall, and evapotranspiration were presented in MIKE SHE to estimate the change of flow in the Swedish Forsmark catchment area. Mernild et al.,(2008) predicted the varied tendency of intra and inter annual

discharge from glacierized Zackenberg River drainage basin in northeast Greenland. Comparing the difference between the present and a climate scenario of 2071 – 2100, the result indicated the increasing tendency of snow melt at this catchment also made an increase of stream flow. Also, Thompson et al., (2013) used MIKE SHE to project the varied trend of flow for the biggest river system in Southeast Asia, Mekong river. Over an area of 795,000 km² and taking into account most of the hydrological factors in this catchment, this MIKE SHE model demonstrated its performance in modelling the impact of climate change for Mekong river.

In summary, the strong points of MIKE SHE discussed in this section, are expected to reduce a part of the uncertainty when evaluating runoff in the rivers of Mexico City, which is a largely undauged catchment throughout its history.

1.6.5 Runoff modeling.

One of the most useful capabilities of hydrologic models in conjunction with GIS technologies is the prediction of surface runoff. The prediction can be used in assessments or prediction of aspects of flooding, and it can aid in reservoir operation and in the prediction of the transport of water-borne contaminants. GIS technologies are used in order to have a better visualization of the spatial data used in hydrological modeling; such as rainfall stations locations, and to process these data as needed, such as trimming the land use data to the desired area of study. [CNA, 2011]

Basin runoff has three components, which can occur separately or simultaneously in varying magnitude, as depicted in Figure 1.15. These components are:

- 1) Surface runoff,
- 2) Sub-surface runoff, and
- 3) Underground runoff.

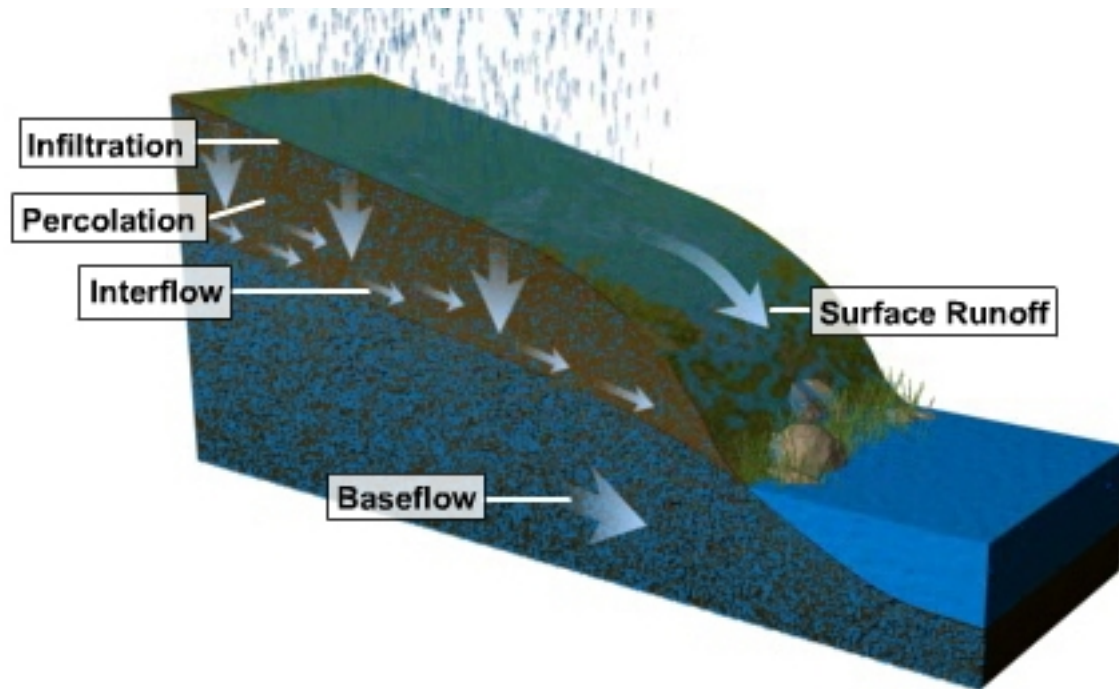


Figure 1.15 Surface runoff, sub-surface runoff and underground runoff or baseflow. [UCAR, 2012]

Some of the most important factors influencing runoff include topography, soil type and land use, area and slope of the basin and the soil moisture conditions preceding the precipitation. Surface runoff, as its name suggests, travels over the ground surface and through the channels towards the outlet of the basin. Surface runoff include:

- Flow in the ground surface,
- Runoff in streams.

Surface runoff commonly occurs when rainfall intensity exceeds the capacity for interception, infiltration and storage. This varies during storm runoff and may cease during its occurrence or suddenly after the storm has ceased.

The surface runoff flows toward the exit of the basin, and part of this is infiltrated into the ground or walls of the channel. Infiltration that takes place in the channels often are referred to as conduction losses. This situation is particularly common in arid, semi-arid and sub-humid climate. For example in arid basins, runoff in small basins is almost always runoff, while in humid areas the sub-surface runoff is predominant. Therefore, the type of drainage occurring in a basin is determined by a combination of climatic and physiographic factors, together with the spatial and temporal characteristics of the rain. [CNA, 2011]

To meet the design flow operation of waterworks and risk analyzes, data of runoff is required where they are located; however, sometimes this information is not available, either due to changes in the conditions of the drainage basin, caused for example by deforestation, urbanization, among others.

Furthermore, urban flooding problems are analyzed through data collection on rainfall events and runoff on surface and in drainage networks. With such available data, the classical approach combines a hydrological model with a hydraulic model – most of the time 1D – able to simulate the runoff and propagation processes. In the case of the Mexico City basin, the runoff on surface and in the drainage networks is not available except for a limited number of gauging stations located in some of the rivers that flow into Mexico City. Therefore, the approach has to be reviewed by implementing an alternative concept. [Vargas and Gourbesville, 2014]

In order to overcome the difficulties and to produce a tool able to support operational management, a potential alternative approach is to implement a deterministic distributed hydrological model. This type of model has the reputation to request a tremendous quantity of data in order to produce simulations and results. However, due to the physically based approach, most of the variables could be reasonably estimated through physically meaningful hypothesis. In addition, several authors have underlined the major importance of an accurate description of the topography properly represented through a DEM. The introduction of additional variables allows improving the efficiency of the model and the quality of the simulations. [Guinot and Gourbesville, 2003]

In the present study, the approach proposed is to use MIKE SHE software to estimate the discharges in several rivers in the East of Mexico City, and apply these discharges in a MIKE 21 model to generate the flood extent and depth, and following, to process this results in GIS to allow for the visualization of the areas with high flood hazard. These maps can be further handled in GIS together with land use data to carry out a detailed assessment of flood hazard in Mexico City for different types of buildings and infrastructure.

Chapter 2. FLOOD, HAZARDS, VULNERABILITY AND RISKS.

Summary.

Risk is the probability that a certain amount of damage occurs in the presence of a hazard (or threat) of a certain magnitude, given a certain vulnerability and exposure of people, infrastructure, property or even human activities to the hazard or threat.

Vulnerability is a measure of the damage that can occur to a certain person, building, construction, real or personal property or human activity for various magnitudes of danger. The exposure is a measure of the degree to which a certain person, asset or activity is subject to the action of danger in terms of their location in time and space. [CNA, 2011]

This chapter gives a general outline of the theory of flood hazards, on vulnerability and flood risks in urban environments specially.

2.1 Flood risk.

A determined area is risky not only in terms of the frequency and intensity of flooding, but also depending on the degree of vulnerability and exposure in which people, buildings, works, goods and activities exist. Generically said, the risk is based on the hazard, vulnerability and exposure (Eq. 3):

$$R = f(H, V, E) \quad (\text{Eq. 3})$$

Where the three independent variables; H, V and E, can have values from 0 to 1. For instance, $V = 1$ is interpreted as the total loss of the asset from the defined danger and $V = 0$ when it is invulnerable to this danger (even when exposed to it). $E = 1$ would imply a maximum exposure (in the case of Hurricane, a location directly on the coastline and $E = 0$ means a lack of exposure).

This way of expressing the concept of risk shows that there are several ways of reducing it. One is reducing the danger (which in many natural phenomena can not

normally be done), the second is reducing vulnerability and the third would be reducing exposure.

Any variables that have a zero make the risk zero, regardless of the value of the other two variables. In reality each of the variables should be viewed as a probability distribution. Some measures of flood control are aimed at reducing the risk (increasing the carrying capacity of the channel without flooding), others may be aimed at the reduction of vulnerability (building the modern equivalent of the stilt houses in the flood zone) and others by reducing exposure (relocating uplands). When assessing and studying the possible types of flood control measures; both structural and non-structural, the points to be discussed should include:

- Type of measure (structural vs non-structural);
- Factor that aims to reduce risks;
- General and functional description;
- Capabilities and limitations;
- Advantages and disadvantages vs other measures.
- Assessing how robust is the measure.
- Potential impacts upstream.
- Possible effects downstream.
- Concentration of initial investment costs and operating expenses.
- Possible combinations with other measures

Furthermore, flooding is a phenomenon that includes precipitation, runoff, flood wave propagation, and flood damage that changes over time and has variations from region to region. It is Influenced by natural conditions, by human activities and a non-sufficient disaster prevention culture. Flood risks are increasing in urban areas due to extended urban spaces, higher exposure to flood risk and new forms of flood damages. [CNA, 2011]

Over the last century, drastic changes have happened to river environments in several cities. Rivers are forced into artificial channels, reducing infiltration, and local communities have a declining trend in considering activities linked to awareness and disaster prevention. Urban flooding is not anymore just a natural phenomenon, the social conditions play an important role and they have spatial and temporal variation. Increasing precipitation episodes that cities are experiencing today due to a big

percentage of impervious areas imposes huge pressure to existing urban drainage systems. [CNA, 2011]

Properties of precipitation (scale, pattern, distribution in time and in space) are also major factors that determinate the magnitude and characteristics of flood as a hazard.

In conclusion, urban flooding brings a risk to an urban system, and it's fundamental to have proper understanding of urban flood risks and to be familiar with the components that construct risk, in order to define a flood management strategy.

2.2 Flood risk management.

Risk management has been recognized as a suitable method for the handling of risks related to natural, environmental or manmade hazards, including floods. Risk management can be more clearly understood if it is defined as a process, which includes three different sets of actions [Plate, 2002]. The first set of actions is needed to operate a system that already exists. When the system becomes insufficient to meet the needs of a population, because of changes in land use, increases in population, climate change, etc., then the planning of a system that is modified to operate in the changed conditions begins. In a third set of actions, which are related to the second set, an adequate design is developed, and the construction of the project is carried out. Hydraulic engineers frequently regard only this set of actions as part of their activity. However, the engineering aspect should be included in the planning for flood risk management, as well as the input from the exposed population and from decision makers throughout the time, as the task of flood risk management is never actually complete. Every generation will need to reassess its options and needs, and decide its own priorities. [Plate, 2002]

A correct risk analysis process should generate hazard or risk maps, which are produced from hydrological models together with Geographical Information Systems (GIS), and which serve to recognize weak points of the flood defense system. For example, the Odra River flood of 1997 in Poland, showed that weak points were not only failures of dikes, but leakage through the dikes and infiltration of flood waters through the drainage system as well. The flood caused 54 deaths and material losses of billions of USD. [Kundzewicz et al, 1997]

According to Plate (2002), flood protection went through a number of development steps in history depending on the type of flood, as a flood, which inundates the lower part of an alluvial river, requires different responses than flash floods, which have high velocities and remarkable erosive forces. Floods in alluvial plains of large rivers have

low velocities in comparison, and the threat to life comes from the broad lateral extent of inundated areas. The earliest populations responded to such floods by relocating their cities and villages out of reach of the highest flood they experienced. However, population pressure and need of farmland often pushed people to move into the flood plains, and to construct dikes to protect themselves. For example, the ancient Chinese started to build dikes alongside their large rivers to protect farmland and villages [CNA, 2011]. Therefore, adjustment to floods depends on a number of variables: the available technology, the accessibility of financial resources, and the urgency of the need for protection, which depends on the perception of a society [Plate, 2002].

Moreover, the evaluation of Flood Risk Management (FRM) frameworks can be done according to the different levels of integration of their elements. Flood risk management covers actions before, during, and after the flood.

2.3 Maturity levels.

A possibility for assessing the different strategies is to use the concept of maturity. The principle is to compare each situation with a reference level, which characterizes the complexity and the efficiency of the implemented flood risk management strategy. These levels are determined according to different characteristics, which are presented within Table 2.1.

The state of maturity means being fully developed or perfected. In general usage, the concept of maturity is being increasingly utilized to map out logical ways to improve an organization's services. It is used in "Best Practice" benchmarks, indicating increasing levels of sophistication and other features [PMI, 2002]. Maturity refers to the degree that an organization consistently carries out processes that are documented, managed, measured, controlled and continually improved (CMMI Product Team, 2002).

Level	Maturity scale	Description
1	Informal	Short-term focus on flood risk management. No standardized flood risk procedures. Ad hoc approaches applied on a case-by-case basis. No understanding or experience of flood risk management. No monitoring or reporting of flood risks.
2	Basic	Knowledge of specific flood risks. Flood risk management procedures are identified and are communicated verbally. High reliance on the knowledge of individuals.
3	Initial	Midterm focus on flood risk management. Flood risk management policy and procedures are implemented partially. Some flood risk management tools and templates are developed. Implementation of flood risk management elements is limited to few stakeholders. Insurance scheme available. Flood maps. Coordination of actions by city governance.
4	Coordinated	Risk is identified. Best practice is incorporated into FRM framework. Capacity building of human resources is on high level. Availability of FRM tools. FRM implementation plan exists. Insurance scheme. Flood maps. Real time systems if needed.
5	Integrated	Resilience concept integrated within the legal framework and at the different operational scales (country to city). Best practice of flood risk management. Learnt lessons are implemented in the FRM framework. FRM is addressing key processes. Insurance scheme. Flood maps. Real time systems if needed.

Table 2.1: Maturity levels of flood risk management at city scale [Batista, Gourbesville, Tessier, 2013]

Maturity is encapsulated within the concept of readiness. The readiness level is a measure that is used to assess maturity of evolving frameworks. This is in addition to the integration of frameworks and implementation of measures. The same approach for the evaluation of technology is done by US Department of Defense (DoD) [TRA Guidelines, 2011], National Aeronautics and Space Administration (NASA) [Sauser et al, 2006] and the European Space Agency (ESA) [Sauser et al 2006].

The system must first be fully mature before it can be ready for use/implementation. Translated to the domain of flood risk management, there is a level that is defining the framework capacity to go for a higher maturity and towards integration.

The highest maturity level for a flood risk management strategy is to introduce and apply the concept of resilience in an active way: the resilience concept is introduced within the legal framework. The readiness level of a flood risk management framework is defined with the legal framework. Before reaching the highest maturity level the framework has to reach a level where all strategies and actions are built in the legal framework.

The move to the integrated level where flood risk management has a resilience approach is done through the implementation of strategies and measures on local scales [Batika, Goubesville, Tessier, 2013].

There are five different levels of maturity:

- 1) First one is an ad-hoc where there is no high-risk perception. The actions are taken in an informal way. The implementation of flood risk management strategies is not assessed for the informal maturity level. Taken actions are without institutional coordination. Risk perception is on the low level.
- 2) Second level of maturity of FRM framework is basic. Here the knowledge is present but just for a specific event. Procedures within flood management cycle are starting to be identified. The risk is known just for the particular events. The reliance on knowledge of individuals is high. The actions taken to manage the risk has low institutional coordination
- 3) Initial maturity has implementation of flood risk management policies. The institutional coordination is present. The coordination is under city governance level. The flood insurance schemes are available as well as flood maps.
- 4) Coordinated maturity level has fully identified flood risks. Flood risk management policy and procedures integrate best practices. FRM tools and templates are available to stakeholders. FRM implementation plan exists with a highly applied capacity building of human resources. Insurance schemes exist and if there is a need in the real time system.
- e) Fifth level of maturity is converging to resilience. On this level the best practice is not just a part of FRM framework but it is also fully integrated. The attitude of learning from past events is dominant. The FRM framework is addressing main problems.

The result of the evaluation presented below shows differences in maturity levels for analyzed cities in a table developed by Batika, Goubesville and Tessier, (2013).

	Beijing (China)	Barcelona (Spain)	Hamburg (Germany)	Nice (France)	Taipei (Taiwan)
FLOOD HAZARD					
Flood control works					
Structural planning and design	4	4	4	4	4
Asset maintenance	3	5	5	4	3
Operations (DSS)	3	4	4	3	3
EXPOSURE					
Land use management					
Flood zoning	3	5	4	4	4
Land use planning	4	4	4	4	4
Resettlement	1	1	1	1	4
VULNERABILITY					
Flood forecasting					
Hydrological and hydraulics models	3	5	5	4	4
Flood hazard maps	4	5	5	5	4
Data acquisition network	4	4	4	4	4
Flood warning & emergency response					
Communication system	3	5	5	4	4
Preparedness exercise	3	4	5	3	4
DSS	3	4	4	4	4
Post flood recovery					
Support services (health, counselling)	3	4	4	4	4
Material support (food, shelter)	3	4	5	4	3
Infrastructure repairs	4	5	5	5	4
Financial assistance& incentives	3	4	4	4	3
Compensation / flood insurance	1	4	2	3	2
Land use management					
Building regulations	3	3	2	3	4
MATURITY LEVEL	3.06 initial	4.11 coordinated	4.00 coordinated	3.72 initial	3.67 initial

Table 2.2 Maturity levels for existing flood management frameworks in European and Asian case studies [Batika, Goubesville and Tessier, 2013].

2.4 Vulnerability and resilience.

Vulnerability is defined as the conditions determined by physical, social, economic, or environmental factors or processes, which are increasing the weakness of a community to the impact of hazard [UN/ISDR, 2004]. Resilience, on the other hand, represents the capacity of an urban system or community exposed to hazard to adapt by resisting or changing in order to reach an acceptable level of functioning, organization and structure [UN/ISDR, 2004].

The defined terminology of vulnerability and resilience is important in the analysis of urban areas and their existing flood risks but there should be a distinction between the flood vulnerability and flood resilience of people on one side and the urban structure on the other side. Resilience does not have a general definition, however, it is increasingly used in integrated urban drainage management, [Ashley et al., 2007; De Bruijn 2004; Klein et al., 1998; Sayers et al., 2003; Sendzimir et al., 2007; Vis et al., 2003;]. The diverse interpretations of resilience reflect the complexity of this concept and made it complex for implementation in integrated urban drainage management.

According to Walker et al., (2004) resilience is defined as the ability of a system to absorb disturbance and to reorganize up to the level of changes that allows the same function, structure, characteristics and feedback. If ecosystem resilience is taken into consideration the first part of the definition is fulfilled in the sense that the ecosystem will accept disturbance by the level that allows persistence.

Moreover, social resilience, as defined by Adger (2000), relates to the ability of human communities to tolerate external stress to services and mechanisms that ensure health care, education, community progress, profit distribution, employment and social welfare.

Concluding, in Mexico City, flood risk management could be considered to be initially mature as institutional coordination is present under city governance level, and flood insurance is available; however, no flood maps for the entire Mexico City exist, only limited zones of flood risk for each state of Mexico, obtained from observations after flood events. Therefore, a flood modeling approach will have to be defined to adapt to this conditions and to the data currently available.

2.5 The flood modeling process.

The technical development of flood maps is an iterative process, and fully depends on local conditions guided by the issues outlined in figure 2.1 [WMO and GWP, 2013]

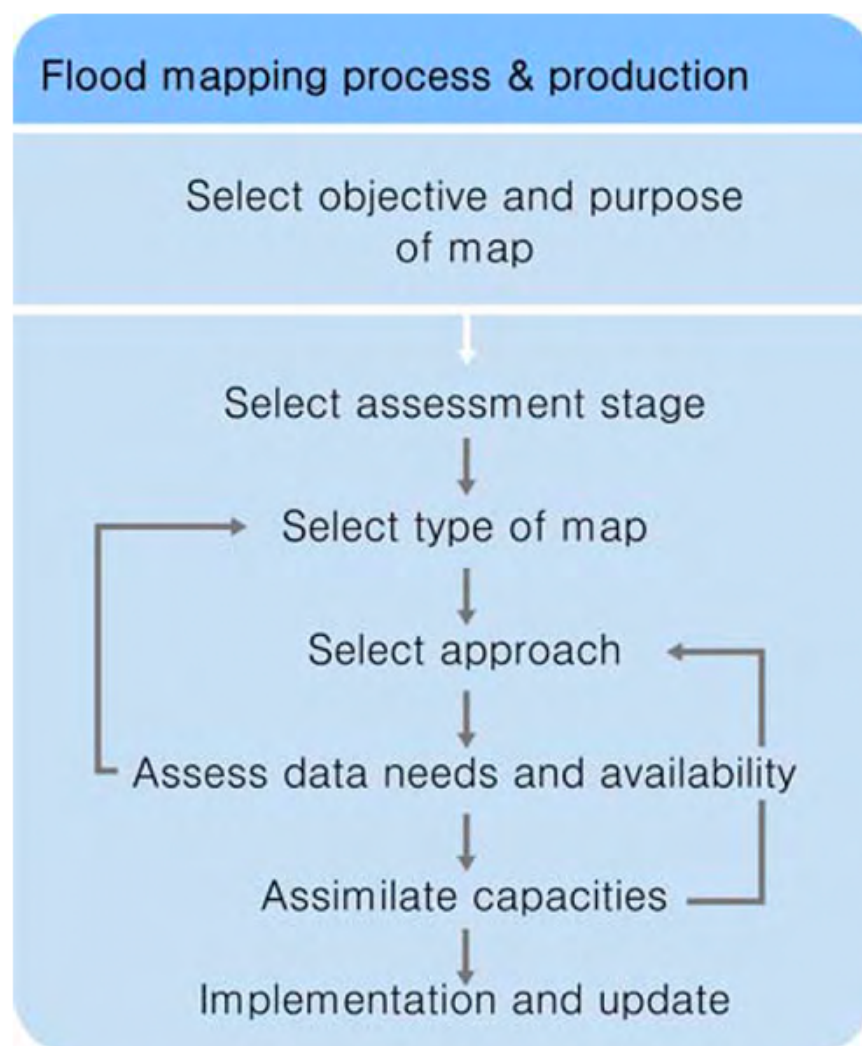


Figure 2.1 Steps of flood mapping process. [WMO and GWP, 2013]

The implementation of flood assessments and development of flood maps require some considerations before the programme launch:

2.5.1 Objectives

According to WMO and GWP (2013), in flood risk management, a concept paper established by the planning team describes the objectives of the flood-mapping programme. In particular the following questions need to be answered:

- Purpose: What are these maps produced for?
- Target audience: Who is using the maps?

- Target area: Which areas are covered? (River basin, particular flood plain, river reach, particular settlement, a whole province etc.

2.5.2 Type of maps

The choice of mapped parameters will depend upon the objectives of the project, the resources available and the potential benefit achievable. The following maps are relevant:

- Event map
- Hazard map
- Vulnerability map
- Risk map

The approach to mapping may be different depending on the stage of mapping (preliminary, general purpose or detailed), the use and the availability of data. Therefore, selection of the type of flood map and its specifications would have to be revisited. [WMO and GWP, 2013]

The key parameters to be included in the maps should be selected and discussed with the users. If external contractors are deployed for the preparation of maps, these specifications becomes very crucial as costs for producing maps with different scales or specification may entail an increase in the magnitude of costs by several orders. [WMO and GWP, 2013]

2.6 Modeling approach and data availability.

Flood hazard maps alone serve many purposes. They can be directly implemented (e.g. in land use planning processes), but are also the main input for vulnerability and risk maps and serve for the production of various end-user instruments. Three different approaches to develop flood hazard maps are:

- Historic approach: Is based on past flood events. Written reports, old maps or photographs or any other document may provide relevant information to delineate flood zones. Currently, satellite imagery supports mapping of near real-time flooding. The historic approach supports preliminary and general purpose flood assessments and their respective maps. [WMO and GWP, 2013]
- Geomorphologic approach: Floods and flows leave distinct marks of past events in the landscape. These marks can be read and interpreted. Flood extent and, to a certain degree, other parameters for the magnitude can also be derived. The

geomorphologic approach serves the preliminary and general-purpose flood assessment and their respective maps.

- Modelling approach: Hydrological and hydraulic models are applied to simulate floods of a particular magnitude occurring in a channel/channel system. In general, the modelling approach serves the detailed flood assessment. [WMO and GWP, 2013]

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

2.7 Data needs and availability

Flood assessments including mapping inherently involves the following data sets:

- Topographic data: Topographic maps with contours, satellite imagery, air photographs, digital elevations models, river cross-sections and similar data. Currently, remote sensing provides data and information which is interesting to explore in developing countries, as suggested by WMO and GWP, (2013)
- Magnitude of hazard: The magnitude of the flood hazard is a function of the physical environment. Data sets include rainfall, snow cover, stream gauge, and hydraulic data (channel geometry, bed roughness etc.).
- Exposure: Exposure is a function of socio-economic activities. Data are: built structures, population, economic value of exposed assets etc. Should be noted that such data are not always readily available. [WMO and GWP, 2013]
- Vulnerability: The characteristics of the exposed assets or processes which make them more or less likely to experience damage or loss. Often such data are not available. As a minimum, vulnerability classes have to be attributed to land-use classes, such as housing estate, industrial complex, transport infrastructure, etc. [WMO and GWP, 2013]

It is desirable that the data in all the above categories are readily available for flood mapping. A comprehensive assessment is required of all available data, their forms and formats of storage, and their data sharing policies. [WMO and GWP, 2013]. As much as possible these data sets should be collated into a single database so that they are available to those who develop the flood mapping programme and who are responsible

for developing specifications for the map products. The comprehensive data assessment should clearly identify gaps. [WMO and GWP, 2013]

2.8 Required capacity

Successful implementation of a flood mapping programme requires human resources, expertise, equipment and supplies. [WMO and GWP, 2013]

The costs of these inputs make up the project budget, however, requirements can be met once the financial resources are tied up. Knowledge and technical expertise, particularly in various fields such as geology, surveying, hydrology, and hydraulic analysis, may be difficult to arrange for a self-sustained long-term flood mapping programme. Therefore, it is important to assess the expertise available within the partner agencies, universities, research institutions and the private sector, and to identify the gaps in skills. [WMO and GWP, 2013]

Figure 2.2 outlines the capacity requirements for flood assessment and map development.

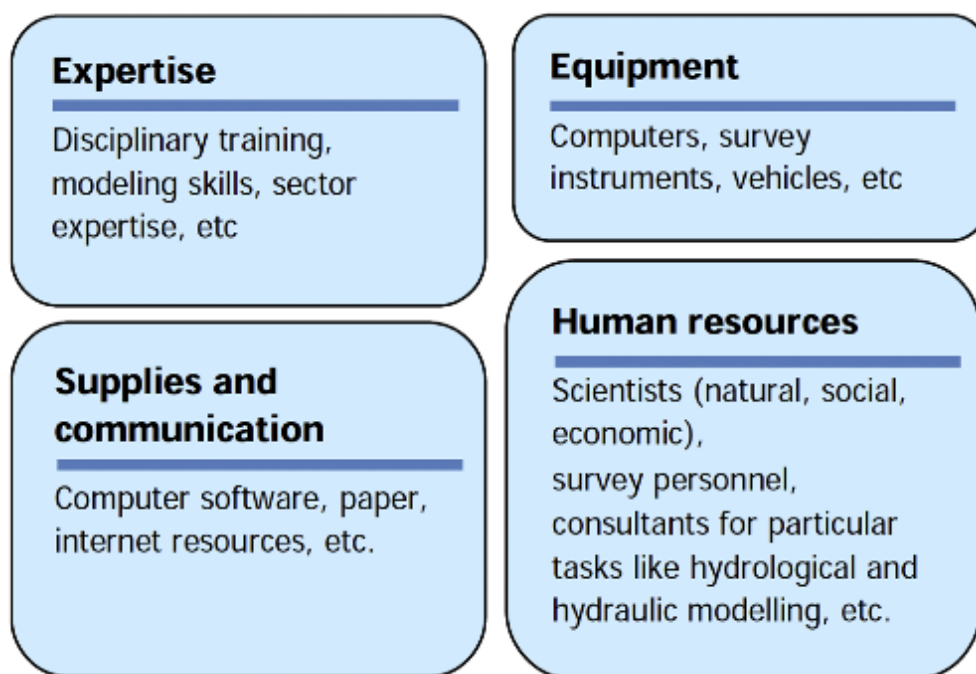


Figure 2.2 The capacity requirements for flood assessment and map development. [WMO and GWP, 2013]

Moreover, a comprehensive capacity building exercise should be planned that would include technical training in all topics where the required expertise is unavailable, such

as analysis of hydrological data, data management using Geographical Information Systems (GIS), hydraulic modelling, geomorphologic field analysis etc.

In the study of flood hazard in Mexico City catchment, objectives have been defined:

- Purpose: To develop flood hazard maps for an economic flood damage assessment.
- Target users: The center for disaster prevention (CENAPRED) and university teams dedicated to the production of flood risk, flood vulnerability and flood damage estimations.
- Area: The Mexico City catchment.

In addition, the type of map produced in this study will be a hazard map in a preliminary stage.

Moreover, the data availability has been defined from the start of this research. Topographic data with digital elevations models and river cross-sections were obtained from the institute of geography and statistics (INEGI).

Information on the magnitude of hazard includes data sets of rainfall, limited data of stream gauge, and hydraulic data (channel geometry, bed roughness etc.).

In regard to exposure, data for Mexico City includes built structures, population, and an approximate economic value of exposed assets etc. Should be noted that such data are not always readily available as in the case of Mexico City, where only the insurance companies have these data and is considered confidential. However, reasonable estimations can be carried out using values of squared meter of construction for different building types

Moreover, on the vulnerability of the exposed assets or processes which make them more or less likely to experience damage or loss is not available in the Mexico City catchment.

Knowledge and technical expertise was assessed in the start of this study and the expertise available within the Mexican agencies, universities, research institutions and the private sector was exploited. The gaps in skills, such as in GIS technology and other technical issues were overcome by training in the University of Nice, France and the I-city Lab, in Nice France. [WMO and GWP, 2013]

2.9 Flood hazard assessments using Topographical LiDAR datasets.

With the advent of GIS based techniques to obtain channel cross-sections, topographic datasets have become essential in flood mapping. The cross-section elevations obtained from topographic datasets are used for hydraulic modeling to produce water surface elevations. Flood extent is obtained by subtracting the topography from the interpolated water surface obtained through hydraulic modeling (Tate et al., 2002). The flood extent is then used to assess what are the assets and the people at risk and to carry out a vulnerability analysis of each.

The use of high-resolution digital elevation models (DEMs) using airborne active sensors is increasing rapidly as these sensor systems become more widely available and cost-effective. These technologies include LIDAR (Light Detection And Ranging, also known as airborne laser scanning) and INSAR (INterferometric Synthetic Aperture Radar, also known as IfSAR). Each technology has strengths and weaknesses and is better suited for different applications.

LIDAR and INSAR are both active sensors emitting a pulse of energy and recording its return at the sensor. LIDAR uses a rapidly pulsed laser rangefinder mounted in a light aircraft with accompanying differential GPS and INS (inertial navigation system) to locate and orient the aircraft. Ten thousand to 30,000 XYZ points are surveyed per second with a spatial precision of a few decimeters, at a cost of a few hundredths of a cent per point. [Norheim et al. 2002]

Following, figure 2.3 depicts the concept of the airborne application, and figure 2.4 presents a LiDAR image created with data collected by the National Geodetic Service:

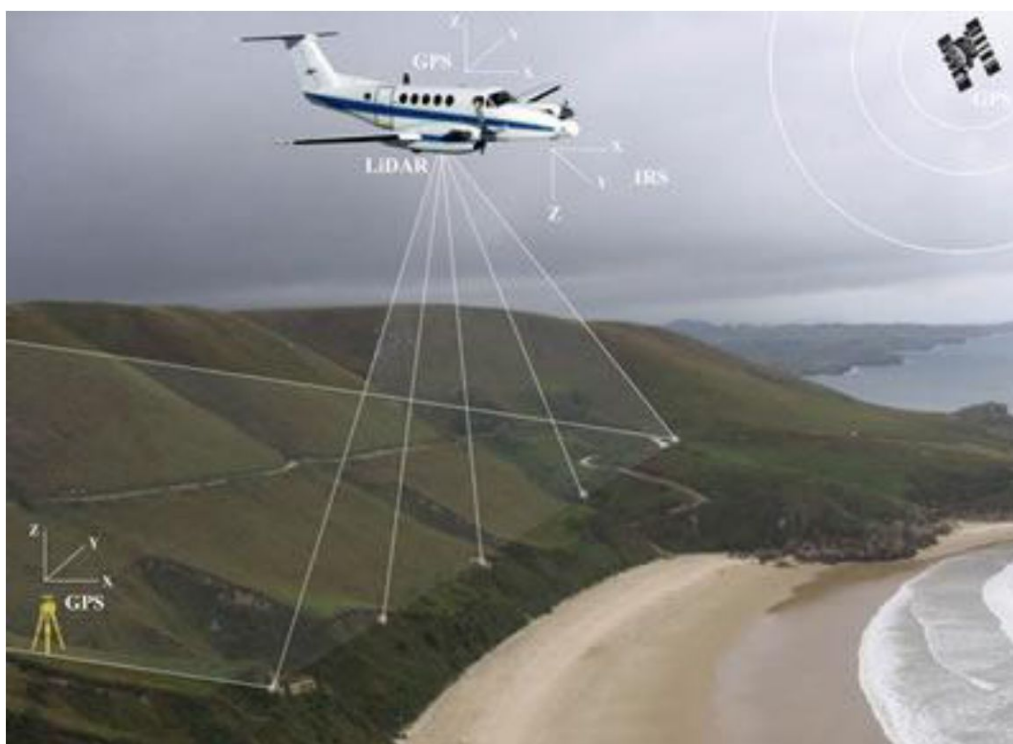


Figure 2.3 Aircraft surveying LiDAR topographic data. [NOAA, 2015]

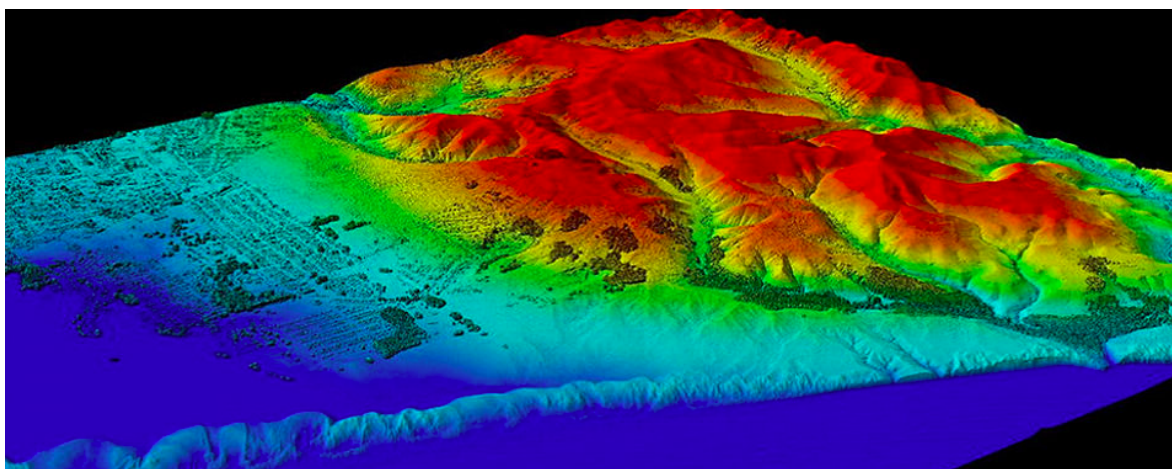


Figure 2.4 A LiDAR image created with data collected by the National Geodetic Service. [NOAA, 2015]

Flying height is on the order of 1,000 m and air speeds are on the order of 100 knots. The surveyed points include ground, vegetation, and structures, and require extensive filtering to extract usable terrain models. In heavily vegetated areas LIDAR systems can be challenged to locate the ground surface. Most LIDAR systems use a near-infrared laser that does not penetrate fog or rain. INSAR bypasses some of these problems. Flying higher and faster than most LIDAR systems, an INSAR-equipped plane can cover large areas. Longer penetrate fog and rain. Extensive development work has

resulted in systems that process data almost as rapidly as it is acquired. [Norheim et al. 2002]

Following, the types of DEM data sources will be explained in detail.

2.9.1 DEM data sources

In order to understand the importance of topography and DEM resolution on flood delineation, it is essential to look at the source of the DEMs that are used for hydraulic modeling. The National Elevation Dataset (NED) provided by the United States Geological Survey (USGS) are the most widely used DEMs in the United States. The NED 30 m resolution DEMs are often obtained from cartography or photogrammetry and are of low quality due to the existence of artifacts [Gesch et al., 2002]. Even though these artifacts are filtered to some extent, these are coarser resolution DEMs with lower accuracy. The DEMs of higher resolution and accuracy are obtained through the LiDAR (Laser Interferometry Detection and Ranging) remote sensing technology. The quality of LiDAR DEMs depends upon the sampling and filtering methods [Chu et al., 2014]. LiDAR technology serves as an accurate survey tool for obtaining highly accurate topographic datasets (Charlton et al., 2003). However, many around the world do not have the resources to obtain LiDAR data, and therefore, DEMs of coarser resolutions like USGS DEMs are used for hydraulic modeling where LiDAR DEMs are unavailable.

Hydraulic modeling and flood mapping using LiDAR data produces more accurate results when compared to other available topographic datasets. This was suggested by comparing the performances of four on-line DEMs (LiDAR, NED, SRTM and IfSAR) on flood inundation modeling and the study was carried out for Santa Clara River near Castaic Junction in southern California and Buffalo Bayou near downtown Houston in Texas [Sanders, 2007]. The results of this study clearly show that LiDAR DEMs represent best the terrain for flood mapping since they have the highest horizontal resolution and vertical accuracy. SRTM DEMs generate the least accurate results due to the existence of radar speckles but their global availability is significant in flood mapping. This study however, did not compare the performance of LiDAR with surveyed data.

In order to evaluate the performance of LiDAR data when compared to surveyed data, Casas et al. (2006) carried out a study of accuracy of topographic dataset sources in hydraulic modeling for Ter River near Sant Julià de Ramis, 5 km downstream of Girona in NE Spain which consisted of Digital Terrain Models (DTMs) from three different sources: high resolution LiDAR, global positioning system (GPS) survey and vectorial

cartography. Hydraulic modeling was carried out using HEC-RAS and water surface elevations and delineated flooded area were analyzed. The contour-based DTM performed with the least accuracy with a variation of 50% in the flood inundation determination. The LiDAR dataset for this study area performed with the highest accuracy with less than 1% variation and GPS-based DTMs produced maps of less than 8% variation from the observed data. The results also showed that the DTM quality and its resolution determine the accuracy of flood predictions. These studies showed that the performance of LiDAR DEMs was superior to the other available DEMs as well as DEMs derived from different sources (GPS survey, photogrammetry and cartography).

In order to evaluate the performance of topographic datasets using a different hydraulic modeling techniques, a study based on remote sensing technology by Schumann et al. (2007) demonstrated the use of synthetic aperture radar (SAR) images of moderate resolution to determine the water line during a flood event. This approach used high resolution LiDAR DEMs to extract elevation values for cross-sections across River Alzette situated downstream of Luxemburg city in England. A regression and Elevation-based Flood Information Extraction (REFIX) model was developed which used remotely sensed flood extents observed during a flood event and linear regression to calculate flood depths. The REFIX model compared the water stages obtained from three different topographic dataset sources. The results showed that LiDAR datasets had the least RMSE (0.35 m) when compared to contour DEM (0.7 m) and SRTM (1.07 m). This study also indicated that flood mapping with coarser DEMs for a small area presented a lot of uncertainties and high-resolution data was required to measure the elevations accurately.

From the studies described above, it can be concluded that LiDAR data is the most accurate topographic data available for hydraulic modeling irrespective of the modeling approach. For these reasons, the LiDAR topographic datasets created by the Institute of geography and statistics of Mexico (INEGI) were selected for the hydraulic modelling of Mexico City [INEGI, 2010].

In the next section, the sensitivity of DEM grid size variation on flood hazard assessments will be discussed, as well as the types of flood hazard models, needed to carry out an analysis of flood vulnerability and a flood risk assessment.

2.9.2 Topography grid size sensitivity analysis.

Regarding the the effect of changing DEM resolution on hydraulic modeling, several studies have been carried out recently which concluded that DEM resolution played a significant role in predicting hydraulic outputs. All these studies suggested that coarser resolution DEMs over-predicted the flood extents and resulted in significant loss of accuracy because coarser DEMs had a significant smoothing effect on the cross-sections. Some of these studies also tried to analyze the causes of the over-prediction.

One of the first studies, by Werner (2001), analyzed the impact of grid size on accuracy of predicted flood areas and showed that hydraulic controls such as embankments have a significant effect on the accuracy of flood extents. Local elevations around the hydraulic controls averaged out on using a coarser resolution DEM while the use of higher resolution DEMs increased the computational time significantly.

This study suggested that one significant disadvantage of coarser resolutions was the inaccuracy in determining correct elevations for bridges, embankments and levees. While this problem could be corrected by using field surveyed elevations and locations for hydraulic controls, the overall effect of decreasing DEM resolutions on predicted flood extents is still significant, and further studies were carried out to evaluate this effect.

For example, in 2005, Haile and Rientjes studied the effects of Lidar DEM resolution in flood modeling for a case study in Honduras. In this study, a DEM of grid size 1.5 meters was created using LiDAR data and resampled to DEMs with decreasing resolutions up to 15 meters. 2-D SOBEK flood model was used to evaluate flood inundation extents. This study concluded that the DEM with the largest grid size predicted maximum inundated area and downstream boundary condition had no significant effect on the flood area. The averaging of small-scale topographic features and arbitrary delineation of flow direction for larger grid sizes were identified as the possible causes for variation in flood area

This study highlighted the significance of DEM resolution for an urban area using a 2-D hydraulic model. However, since 2-D hydraulic modeling is more complex than 1-D modeling, and 1-D HEC-RAS modeling is used more frequently in the world, there has also been interest to determine the impact of DEM resolution for 1-D hydraulic models. For instance, a study at Eskilstuna River in Sweden was carried out by Brandt (2005) to show the effect of different DEM resolutions on inundation maps using 1-D HEC-RAS. The results showed that higher resolution DEMs produced more precise flood maps.

However, all the cross-sections used in the hydraulic model were determined from high resolution DEMs. Resampled DEMs were used only to calculate the inundated areas after the water surface elevations were generated from HEC-RAS.

Figure 2.5 illustrates the maximum inundation area for two applied DEM's in the study by Haile, A., & Rientjes, T. (2005).

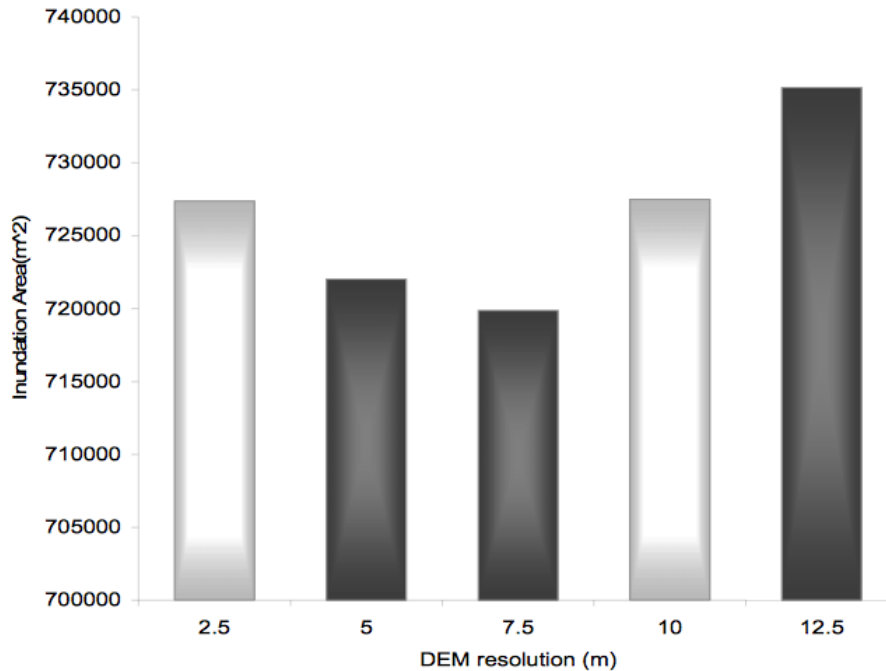


Figure 2.5 Maximum inundation area variation with DEM resolutions. [Haile, A., & Rientjes, T., 2005]

Since the same discharge hydrograph was introduced for the upstream boundary condition in this study, equal volumes of water were expected to be stored in the model domain provided the same upstream and downstream boundary condition was introduced. Even when cross sectional areas increase with increased element size, it was assumed that such effect can be ignored since inflow and outflow boundary elements are of equal size. This is to satisfy the law of mass conservation: for a certain time period, the inflow minus the outflow must be equal to the change in storage. Therefore, the authors expected a larger flood extent usually associated with a smaller flood depth. Following this reasoning, it was surprising that this was not observed in figure 2.6 and 2.7. For the 15 m resolution DEM as compared to the 5 m DEM, the significant increase in inundation extent and depths were found to be extremely large. [Haile, A., & Rientjes, T, (2005)]

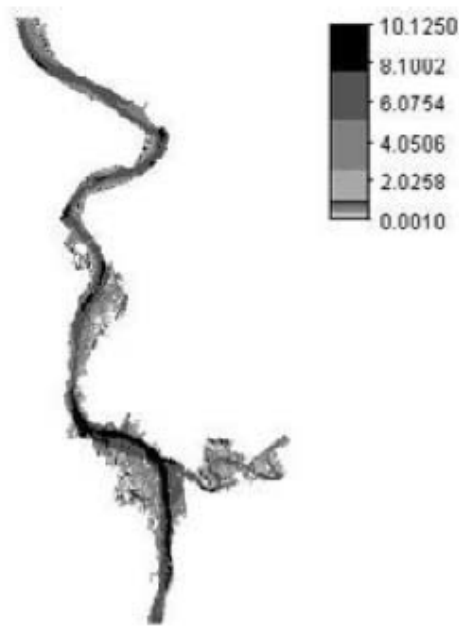


Figure 2.6 Maximum flood depths for 5 m resolution.

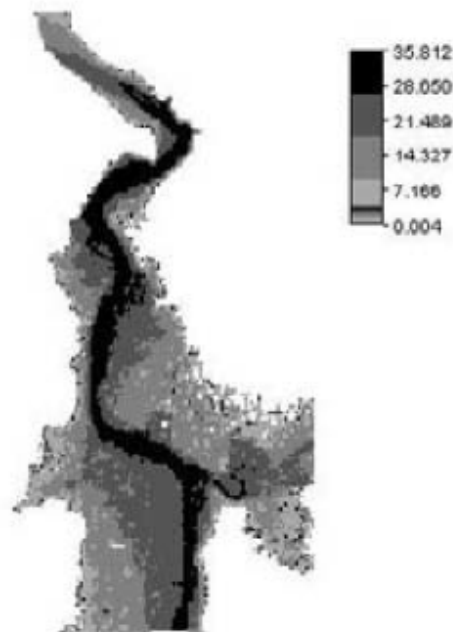


Figure 2.7 maximum flood depths for 15 m. Resolution. [Haile, A., & Rientjes, T. ,2005].

In a more recent study, Manfreda et al, (2011) applied a method for delineation of flood prone areas on 11 sub-catchments in the Arno River in Italy, with areas ranging from 489-6,929 km² utilizing DEMs of different resolutions with cell sizes ranging from 20-720 m. According to the authors, the method is sensitive to the DEM resolution, but a cell size of 100 m was sufficient for good performance for the catchments investigated. Adopting DEMs from different sources, such as the shuttle radar topography mission (SRTM) DEM, ASTER global DEM (GDEM), and national elevation data tested the procedure. This experiment highlights the reliability of the SRTM DEM for the delineation of flood-prone areas.

Furthermore, Van de Sande et al. (2012), studied the sensitivity of Coastal Flood Risk Assessments to Digital Elevation Models in the Lagos State in Nigeria. The authors stated that in low lying deltaic areas, the land elevation variation is usually in the order of only a few decimeters, and an offset of various decimeters in the elevation data has a significant impact on the accuracy of the risk assessment.

Publicly available DEMs are often used in studies for coastal flood risk assessments, and the accuracy of these datasets is relatively low, in the order of meters, and is

especially low in comparison to the level of accuracy required for a flood risk assessment in a deltaic area.

For a coastal zone area in Nigeria (Lagos State) an accurate LiDAR DEM dataset was adopted as ground truth concerning terrain elevation. In this study, the LiDAR DEM was compared to various publicly available DEMs. The coastal flood risk assessment using various publicly available DEMs was compared to a flood risk assessment using LiDAR DEMs.

It can be concluded that the publicly available DEMs do not meet the accuracy requirement of coastal flood risk assessments, especially in coastal and deltaic areas. For this particular case study, the publically available DEMs highly overestimated the land elevation Z-values and thereby underestimated the coastal flood risk for the Lagos State area. The findings are of interest when selecting data sets for coastal flood risk assessments in low-lying deltaic areas. More recently, Saksena (2014) carried out a study to determine a relationship between DEM resolution and accuracy in flood inundation mapping. The study areas were classified into two different groups based on the land use characteristics and size to account for different characteristics. For each study area, cross-sections along one station were presented for the original LiDAR and for a 100 m resolution resampled DEM. The average water surface elevations, inundation area and percentage change in inundated area for DEMs of increasing grid size or decreasing resolution for study area was calculated and compared with each grid size. The results showed that inundation area increase when increasing the grid size as shown in figure 2.8

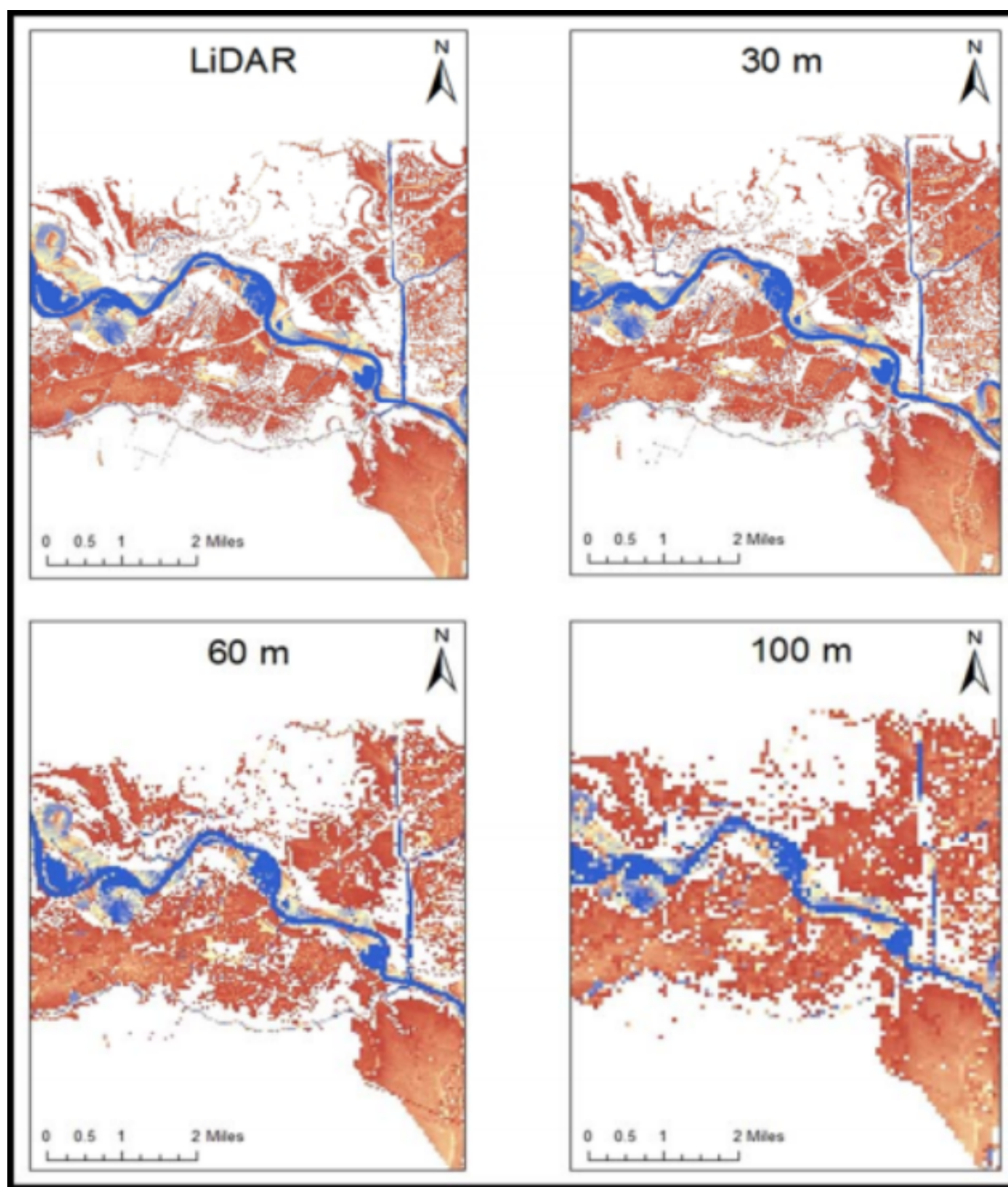


Figure 2.8 Flood maps generated from different resolution DEMs [Saksena, 2014]

The comparisons for Brazos River show no significant changes in the overall quality of the flood maps and extents on using coarser resolutions DEMs. The main channel and flood plain morphology is also not effected significantly. However, there is a difference of about 30 km² in the inundation areas obtained from the LiDAR and a 100 m DEM, which is an over-estimation even though the percentage change in inundated area is not large. [Saksena, 2014]

Moreover, to understand the causes for the over-prediction of flood extents by coarser resolution DEMs, a study on the effect of cell resolution on depressions was carried out by Zandbergen (2006) for a 6 m LiDAR DEM in Middle Creek, North Carolina. According to the author, a proper understanding of the occurrence of depressions is necessary to understand how they affect the processing of a Digital Elevation Model (DEM) for hydrological analysis.

While the effect of DEM cell resolution on common terrain derivatives has been well established, this is not well understood for depressions. The more widespread availability of high resolution DEMs derived through Light Detection and Ranging (LIDAR) technologies presents new challenges and opportunities for the characterization of depressions. A 6-meter LIDAR DEM for a study watershed in North Carolina was used to determine the effect of DEM cell resolution on the occurrence of depressions. The number of depressions was found to increase with smaller cell sizes, following an inverse power relationship. Scale-dependency was also found for the average depression surface area, average depression volume, total depression area and total depression volume. Results indicate that for this study area, the amount of depressions in terms of surface area and volume is at a minimum for cell sizes around 30 to 61 meters. In this resolution range there will still be many artificial depressions, but their presence is less than at lower or higher resolutions. At finer scales, the vertical error of the LIDAR DEM needs to be considered and introduces a large number of small and shallow artificial depressions. At coarser scales, the terrain variability is no longer reliably represented and a substantial number of large and sometimes deep artificial depressions are created.

The results presented support the conclusion that the use of the highest resolution and most accurate data, such as LIDAR- derived DEMs, may not result in the most reliable estimates of terrain derivatives unless proper consideration is given to the scale-dependency of the parameters being studied.

Furthermore, Agular et al. (2005) investigated and published the effects of terrain morphology, sampling density, and interpolation methods for scattered sample data on the accuracy of interpolated heights in grid Digital Elevation Models (DEM). Sampled data were collected with a 2 by 2 meters sampling interval from seven different morphologies, applying digital photogrammetric methods to large scale aerial stereo imagery (1:5000). The results obtained allow observing the possibility of establishing empirical relationships between the RMSE expected in the interpolation of a Grid DEM and such variables as terrain ruggedness, sampling density, and the interpolation

method, among others that could be added. Therefore, it would be possible to establish a priori the optimum grid size required to generate or store a DEM of a particular accuracy, with the economy in computing time and file size that this would signify for the digital flow of the mapping information.

In the following section, the types of flood models are presented and explained.

2.10 1-D and 2-D flood hazard models

Flood models can be categorized into several types depending upon their data requirement, level of complexity of the underlying equation, and the resolution. Two important distinctions between models are the spatial aspects and input requirements. Models can be identified based on their spatial aspect of field characteristics:

- One dimensional (1D) models are simplified models, which characterize the terrain through a series of cross sections and calculate the aspects like water depth and flow velocity towards the direction of flow. Examples of these models are the Beach profile model, HEC-RAS, LISS-FLOOD, and HYDROF [Jha et al. 2012]. 1D model simulates the hydraulic components generally by solving the one dimensional St Venant equations that can express both continuity and the 1D section averaged Navier Stokes Equations (4,5).

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \quad \text{Eq. 4}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}(uQ) + gA\left(\frac{\partial h}{\partial x} - S_0\right) + gAS_f = 0 \quad \text{Eq. 5}$$

- Two dimensional (2D) models calculate the flow in both spatial dimensions with conditional uniformity. They are useful for modeling areas of complex topography such as wider floodplains but require high quality data and long computation time. Examples of 2D model are MIKE 21, TELEMAC 2D, SOBEK 1D2D, Delft 3D etc. This kind of model is developed based on solving the bi-dimensional shallow water equations (2D Saint Venant equations) which simulate flow components in the form of mass and momentum conservation (Equation 6, 7, 8) [Ahmad & Simonovic, 1999]

Continuity:
$$\frac{\partial \zeta}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = 0 \quad \text{Eq. 6}$$

$$\begin{aligned} \text{Momentum_X} \quad & \frac{\partial p}{\partial t} + \frac{\partial}{\partial x} \left(\frac{p^2}{h} \right) + \frac{\partial}{\partial y} \left(\frac{pq}{h} \right) + gh \frac{\partial \zeta}{\partial x} + \frac{gp \sqrt{p^2 + q^2}}{c^2 h^2} - \frac{1}{\rho_w} \\ & \left[\frac{\partial}{\partial x} (h\tau_{xx}) + \frac{\partial}{\partial y} (h\tau_{xy}) \right] - \Omega q - fvv_x + \frac{h}{\rho_w} \frac{\partial}{\partial x} (p_a) = 0 \end{aligned} \quad \text{Eq. 7}$$

$$\begin{aligned} \text{Momentum_Y:} \quad & \frac{\partial p}{\partial t} + \frac{\partial}{\partial y} \left(\frac{p^2}{h} \right) + \frac{\partial}{\partial x} \left(\frac{pq}{h} \right) + gh \frac{\partial \zeta}{\partial y} + \frac{gp \sqrt{p^2 + q^2}}{c^2 h^2} - \frac{1}{\rho_w} \\ & \left[\frac{\partial}{\partial y} (h\tau_{yy}) + \frac{\partial}{\partial x} (h\tau_{xy}) \right] - \Omega q - \frac{h}{\rho_w} \frac{\partial}{\partial y} (p_a) = 0 \end{aligned} \quad \text{Eq. 8}$$

Moreover, there are two approaches used in modeling flood events that depend on the needs of the user: probabilistic forecasts and runoff routing. In the probabilistic approach, statistical distribution is used to determine the uncertainty in model inputs. A rainfall–runoff approach provides complete hydrographs of the basin, by dividing it into sub-divisions and run offs routed from excess rainfall within each one. It is also advantageous for spatial distribution of rainfall over larger areas and, as a result, is helpful in prediction for larger basins. [Jha et al. 2012]

Flood hazard simulation models are generally expensive to buy and require expert knowledge to use to get appropriate outputs. It is important for any flood manager to understand the importance of adopting an appropriate model based on the information needs for planned risk reduction and availability of resources. However, not all developing countries can afford such expensive models for flood simulation. It is therefore important to have knowledge of the alternatives available in the form of freely available simulation software.

For the specific case of the present analysis discussed in this thesis, the modeling systems MIKE 21 and MIKE SHE as well by DHI was provided to the Université de Nice Sophia Antipolis, France. [DHI, 2012] Therefore it was this 2D model that was used to analyse the flood hazard in Mexico City.

2.11 Vulnerability and risk mapping

The flood risk assessment involves the survey of a real or potential flood in order to estimate the actual or expected damage for making recommendations for prevention, preparedness and response. This consists of evaluation of risk in terms of expected loss of lives; people injured, property damaged and businesses disrupted. Risk can be

defined as the product of hazard and vulnerability and can be mathematically expressed for a given event in a particular area and time period. [UNDHA 1992].

According to WHO (1999), evaluation of hazards and vulnerability assessments should be carried out as parallel activities, in a consistent manner, so that results may be combined and comparable. For example, two cities may have equal vulnerability, but could have different exposure to the hazard, depending on their elevation.

The main problem in evaluation of flood hazard is the availability of organized data, (especially in developing countries) and the cost and effort needed to acquire data.

As stated before, in most cases flood risk assessments are performed based on direct damages. Indirect damages are often ignored leading to underestimation of the total cost of flood damage. However, getting appropriate data for indirect damage assessment can be difficult and the main problems are to measure accurately the effects on the economy and impacts on infrastructure and communication disruption [WHO, 1999]. Furthermore, historical data do not separate the total loss into direct and indirect losses and discrepancies in data can arise when gathered on a survey basis. Moreover, affected people and companies may not be willing to cooperate in the disclosure of financial losses.

However, according to Jha et al. (2012), ‘the assessment of second order risks is achievable if appropriate data is available. In order to perform a comprehensive risk assessment, thus reducing the difference between actual and estimated damage assessment, integration of primary and secondary sources of damage assessment and risk evaluation are necessary.’ Drainage and transportation systems may be disrupted by the large amount of debris left by flooding. It may also cause fires and electrical short circuits. In addition, floodwater may also contain toxic materials, leading to pollution of the local environment.

Vulnerability is defined as ‘the degree to which a system (in this case, people or assets) is susceptible to or unable to cope with the adverse effects of natural disasters’. It is a function of the character, magnitude and rate of hazard to which a system is exposed, its sensitivity (the degree to which a system is affected, adversely or beneficially) and its adaptive capacity (the ability of a system to adjust to changes). The types of vulnerability and the factors that increase their exposure are presented in Table 2.3

Types of Vulnerability	Exposure factors
Individual or household vulnerability	Education, age, gender, race, income, past disaster experience
Social vulnerability	Poverty, race, isolation, lack of social security services
Institutional Vulnerability	Ineffective policies, unorganized and non-committed public and private institutions
Economic Vulnerability	Financial insecurity, GDP, sources of national income and funds for disaster prevention and mitigation
Physical Vulnerability	Location of settlement, material of building, maintenance, forecasting and warning system
Environmental Vulnerability	Poor environmental practices, unprecedented population growth and migration
System vulnerability	Utility service for the community, health services, resilient system
Place Vulnerability	Mitigation and social fabric

Table 2.3 Types of vulnerability and the factors affecting their rate of exposure [Jha et al. 2012]

Some of the main factors which increase vulnerability to urban flooding in developing countries have been found to be poverty; poor housing and living conditions, lack of preparedness, increasing population, development of settlements in hazard prone regions, poor maintenance of drainage structures and lack of awareness among the general population. Therefore, a vulnerability assessment is carried out in order to identify the most vulnerable sections of the society and to prioritize the assistance by channeling resources. [Jha et al. 2012]

Undertaking a vulnerability assessment requires considering the location of the area, the resources under threat, the level of technology available, the lead-time for warning and the perceptions of residents about hazard awareness.

In order to reduce vulnerability and enhance capacity building, mapping vulnerability can help the policy makers and managers by identifying the areas of highest susceptibility and impact. [Jha et al. 2012] Flood management in an area can be made highly effective through vulnerability zoning, in which areas are classified from higher to lower levels of vulnerability. This can further help in the proposition of flood defense mechanisms, effective flood control measures, evacuation planning and flood warning.

Table 2.4 summarizes the methods selected by Villagrán de Leon (2006) that can be used for vulnerability at different scales of interest, from national down to local.

Serial number	Methods	Remarks
A	National Level	
1	Disaster Risk index by BCPR-UNDP	Based on historical vulnerability, for example mortality and level of damage; simple and straightforward
2.	Hot spot model by World Bank	Calculated to get vulnerability coefficients; based on disaster related mortality and losses
3	Composite vulnerability index for small island states	This method is event specific.
4	Small island states: natural disaster vulnerability indicator	Uses five specific indicators of vulnerability; representation via scale of 1-4, (1 being of highest vulnerability and 4 the lowest)
B	Megacity level	
1	Mega city level vulnerability assessment by Munich Re	It is important for understanding the level of vulnerability of the existing infrastructures and population; does not take into account historical disasters
C	Local Scale	
1	Vulnerability assessment at local level	Data acquired from local offices at municipal level, questionnaires and national archives, where available; several factors are used to assess vulnerability
2	Household sector approach	Effective for high magnitude events; surveys individual households to gather data about their level of vulnerability
3	Vulnerability at community level	This approach provides a comparative vulnerability analysis between communities in an area; data is primarily collected through questionnaire surveying and interviews
4	Normalizing vulnerability and risk community comparison	Vulnerability is accessed at town and city level by integrating data from aggregation of parameters at this level
5	Holistic approach	Method combines the approach as represented by exposure rate, social fragility and lack of resilience measures; easy to apply in cities but needs specific survey to gather information

Table 2.4 Vulnerability assessment methods at different scales: [Villagran de Leon 2006]

2.11.1 Flood risk maps

Areas at risk of flooding can be dynamic in nature. With a changing level of development, the nature and degree of risk also changes. Flood risk increases mainly because of an increased level of exposure of the elements under threat. For example, there are occasions when infrastructure or other buildings are constructed in areas already at risk, thereby automatically falling within a risk zone. [Jha et al. 2012]

It is also possible that at the time of construction, the assets and infrastructures are thought to be outside the risk region, but there are newer effects arising from changing land use. These include increasing rates of runoff, lack of drainage systems, lack of storage systems, overwhelming amounts of rainfall leading to overflow, and the

channelization of rivers, which may reduce the amount of discharge they can accommodate.

These factors can increase the number of elements at risk of flooding in an area. Therefore, several authors suggest that continuous updating and monitoring of risk maps is of high most importance for proper flood risk management, as decision-makers need up-to-date information in order to allocate resources appropriately. [Jha et al. 2012]

Hazard maps provide information on the probability of flooding for different return periods, as well as the depth and extent of the floodwater in the affected area. Changnon (2003) argued that, even without an increase in flood hazard over time, the impact of flooding has risen (and will continue to rise) because of the increased exposure of primary and secondary receptors. Furthermore, Moors (2005) found other factors that are potentially quite significant, but may be difficult to quantify: changing risk due to societal factors, land surface alteration, the dynamic nature of social systems in general and societal vulnerability to flooding. However, several sources of uncertainty are present in the calculation of risk, as flood damage prediction depends on approximations in hydrological and hydraulic models, including the neglected contributions to flooding such as debris, structure failures, and local storm water drainage. Also, there may be differences of opinion when decision-making for assessing the areas of highest risks. It is, therefore, important to analyze these areas to an appropriate level, in order to identify the best strategies for risk reduction. This requires that special attention is given to the magnitude of flooding (from the flood hazard maps) and the identification of the vulnerable elements (from the vulnerability assessment criteria). The spatial distribution of vulnerable elements shown by the flood risk map will then identify clearly the areas of concern and their level of risk. The risk map is the core component of the flood risk management strategy. [Jha et al. 2012]

2.11.2 Considerations for flood risk mapping

As stated before, risk evaluation is the basis for the design of methods to prevent, mitigate and reduce damages from natural disasters. Although there are several available methods for assessment of risk, several researchers have observed that in many cases societies prefer to set arbitrary standards as the basis for risk mitigation. Without a clear and detailed evaluation of risk, those responsible for planning will have inadequate information for allocation of resources. This makes it more important to have

a standard method for preparation of flood maps as a utility tool for the decision makers. Table 2.5 below presents essential issues for flood risk mapping.

Actions	Considerations/ operations	Outputs / benefits
Data Collection and Integration	<p>Actual event data, historical data, socio-economic and physical data</p> <p>Sources: local municipalities, regional or national data archives, international organizations like WMO, EM-DAT, existing vulnerability curves for different countries</p> <p>Field Surveying</p> <p>Hypothetical scenario generation for modeling vulnerability</p>	<p>Output in the form of database</p> <p>Important for integration of data from different sources and for future vulnerability analysis of the elements at risk</p>
Generation of stage damage functions or vulnerability curves	<p>Depth of flood water for different return periods</p> <p>Value of the elements at risk depending on their location, condition, material of construction, number of floors, and existence of cellars</p> <p>Extracting data by graphically representing the percentage of damage of the elements at risk to depth of flood water due to lack of resilience and adaptive capacity</p>	<p>Vulnerability curves are important for identifying the level of damage that has been (or can be caused by) different water depths</p>
Conversion of depth-damage-curves to vulnerability maps	<p>Importing data to GIS software (Arc GIS (ESRI), ILWIS (Integrated Land And Water Information System; open source), GRASS (Geographic Resource Analysis Support System; open source)</p> <p>Map classifications based on high, medium and low vulnerability</p>	<p>Conversion of results to an accessible, visual format as maps</p> <p>Essential for illustration of zones of high, medium and low vulnerability for action prioritization</p>
Using vulnerability maps for risk assessment	<p>Integration of hazard maps and vulnerability maps to produce risk maps</p>	<p>Output is in the form of maps showing high, medium and low risk areas</p> <p>Utility tool for decision making to local, regional, national and global authorities</p>

Table 2.5 Considerations for flood risk mapping [Jha et al. 2012]

2.11.3 Determination of flood zones

Understanding how an area may be affected by a flood event enables policy and decision makers to design appropriate development frameworks and carry out development that takes into account the potential impacts of flooding. Understanding flood events is often framed within the context of risk or the probability of a particular type of event occurring. This risk or likelihood of an event is then expressed spatially to detail the anticipated extent of floodwaters.

Therefore, the preparation of flood zones is the most common method to classify thresholds of probability and the associated spatial implication. For example, common storm probability thresholds are:

- Less than 0.1 percent (low probability of flooding)

The chance of flooding in this area is less than 0.1 percent (1 in 1000) per year

- Between 0.1 percent and 1 percent (medium probability of flooding)

The chance of flooding in this area is greater than 0.1 percent (1 in 1000) but less than 1 percent (1 in 100) per year

- Between 1 percent and 5 percent (high probability of flooding)

The chance of flooding in this area is greater than 1 percent (1 in 100) but less than 5 percent (1 in 20) per year

- Greater than 5 percent annual exceedance probability (AEP) (functional floodplain, or floodway)

The chance of flooding in this area is greater than 5 percent (1 in 20) per year.

These thresholds serve as a framework for planners and decision makers to determine appropriate development policy using a risk based planning approach. Understanding how these thresholds relate to a geographical area represents the ‘appraising’ risk step. [Jha et al. 2012]. It should be noted that a range of natural and human-induced factors influences these thresholds. Areas that have a greater probability of being affected by flooding, as described above, are often situated within a natural catchment area near a watercourse. Human-induced factors may include the level of development in a

particular area and the hard surfaces present which impact the flow of urban runoff and in turn an areas ability to cope with a particular type of flood event. Therefore, land use planners need to understand that all areas will fall within one or other of these flood zones and that there are relationships between each of the zones. These relationships will change over time as natural processes evolve and human settlement and development increase. Moreover, flood zones provide a spatial framework in which development can occur and are developed on the basis of flood hazard mapping and risk. Flood zoning allows greater flexibility in planning by restricting the development of highly vulnerable uses like residential buildings in high-risk areas but permitting less vulnerable uses in lower risk areas. [Jha et al. 2012]

2.11.4 Determination of appropriate land uses.

Appropriate land use is determined based on the vulnerability to flooding of the building type or its occupational use. For example, a hospital is typically considered a highly vulnerable use and, therefore, it is more appropriate to locate hospitals in areas at lower probability of flooding.

Even when the approach to vulnerability is commonly considered from a human and economic perspective, when determining appropriate land uses, consideration must be given also to potential environmental impacts [Jha et al. 2012]. Furthermore, land use plans incorporating flood risk management through the creation of flood zones, and development frameworks that specify appropriate land use provide guidance about the type of development that can occur and where it can occur. However, this guidance has no effect if there is absence of regulation to legally control development. Such regulations will need to interface with existing land use control, planning and building control legislation and will be limited by the strength of current land use planning procedures [Jha et al. 2012].

Typically regulations include:

- The appropriate uses for new development permitted in a designated zone
- The requirement for flood risk assessment for all new developments
- Minimum design standards for permitted development within a designated zone
- Compulsory drainage and surface water management plans
- Presumption against reconstruction of damaged dwellings within designated zones
- Compulsory retrofitting of flood protection measures.

In the case of Mexico City catchment, the land use regulation is in a starting point of development, in addition, new developments do not require a flood risk assessment, and drainage and surface water for new developments does not take into account the increase in drainage and in runoff. Therefore, land use planners need to study the result of the flood risk assessments and the flood zones determined by these studies. Also understand the change over time as natural processes evolve and human settlements increase. Flood zoning will someday permit the restriction of the development of vulnerable uses like residential buildings in high-risk areas thus decreasing the damage of floods.

2.12 Direct impacts of flooding.

Primary receptors of the direct impacts of flooding on include people, the urban built environment, infrastructure, and family assets.

2.12.1 People

According to Jha et al. (2012), floods around the world signify a number of threats to human life, health and well-being. In 2010, flood disasters killed over 8,000 people directly worldwide as reported by local authorities. However, while economic losses rise, direct deaths from flooding may be declining over time as measures to prevent flooding are put in place, especially in developed countries. This can be inferred from figure 2.9

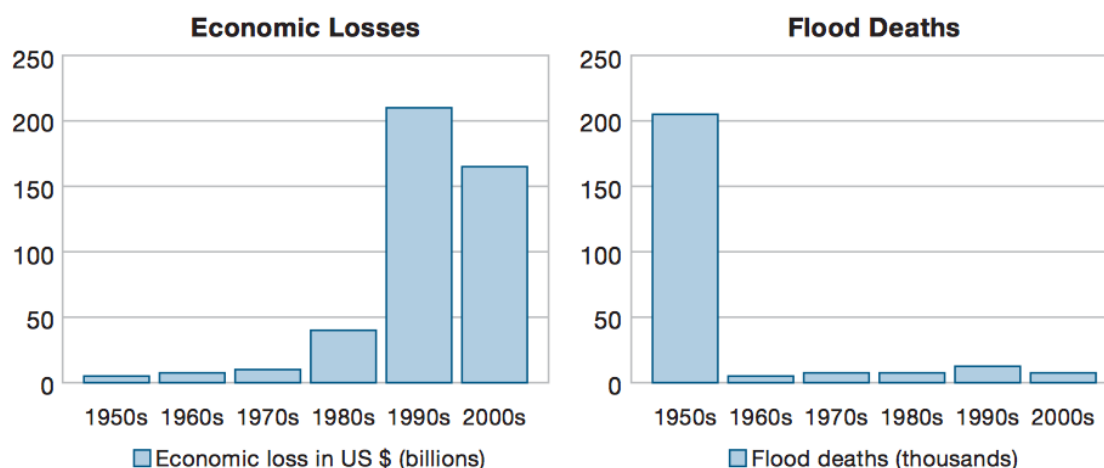


Figure 2.9 Economic losses in US billions and deaths worldwide. [Du et al., 2010]

According to Du et al. (2010), most deaths happen during flash flood events. Furthermore, Jonkman and Kelman (2005) stated that two thirds of direct deaths from flood events are caused by drowning, and one-third by physical trauma; heart attack,

electrocution, carbon monoxide poisoning or fire. In developing countries most of the flood deaths have been found to be caused by diarrhea and other water-borne diseases, or from drowning and snake bites. In Vietnam for example, electrocution causes most of the deaths in the immediate aftermath of flooding, followed by respiratory diseases, pneumonia and exposure to cold. Diarrhea-related deaths are caused by a lack of pure drinking water, incorrect storage and handling of drinking water, poor hygiene practices and the often deterioration of sewage and sanitation facilities which lead to the contamination of drinking water in flood affected. Some of these deaths can occur during the period following the reported flood and for this reason are not necessarily recorded in disaster databases. [Jha et al. 2012]

Over the past three decades more than one hundred million people each year have been affected by floods, which have forced governments to take action towards reducing these statistics. The population affected has increased from approximately four million a year in 1950, to more than one percent of the global population today. [Du et al., 2010]

Flood-related injuries commonly reported include sprains and strains, lacerations, contusions and abrasions. People may injure themselves attempting to escape, either by objects being moved by fast-flowing water or by structures collapsing (Du et al. 2010). In the pre-onset phase of flooding, flood-related injuries can also happen as individuals try to remove their family or valued possessions from the approaching waters (Ahern et al. 2005). Post-onset injuries usually occur when residents return to their homes and businesses to start the recovery and reconstruction process. According to Few et al. (2004), these injuries are not monitored adequately, which makes it difficult to quantify the true magnitude of ill health due to flood events.

The mental trauma of flooding can result in severe psychological effects in some individuals and can be caused by witnessing deaths, injuries and destruction of the home. Moreover, grief and material losses, as well as physical health problems, can cause depression or anxiety. According to Ahern and Kovats (2006), three types of mental health issues have been noted: common mental health disorders; posttraumatic stress disorders (PTSD) and suicide. The poorest members of the community, which are the most vulnerable, can also be the worse affected. Of these, the elderly and the youngest members of the community require special help and assistance, and research has found that children and the elderly are more likely to die from drowning, than are adults [Bartlett, 2008].

2.12.2 Buildings and contents

Buildings and their contents are directly and indirectly affected by flooding in a variety of ways. Direct impacts are the physical damage caused to buildings and their contents, and indirect damage includes the loss of industrial or business activity. Jha et al. (2012) stated: 'the impact of flooding on housing and households can be devastating. Fast-flowing floodwaters are capable of washing away entire buildings and communities. Depending on their form of construction and characteristics of the flooding, many buildings may survive the flood but will be damaged quite extensively by the corrosive effect of salinity and damping, and be in need of substantial repairs and refurbishment'. Furthermore, impacts on businesses range from direct physical impacts to indirect effects, such as disruption of supply chains. [Bartlett, 2008].

The speed of flooding is an important factor of the extent of the damage. While flash flooding can completely destroy properties or cause irreparable structural damage, slow rising floods can damage buildings when water soaks into the fabric of the building elements causing them to deteriorate. Water can also soak upwards through building materials by capillary action. Furthermore, water pressure of standing water can cause building elements to fail or structures to collapse. Also, water can cause failure of electrical systems resulting in secondary damage.

In fast floods, water that is moving exerts a great lateral pressure on building elements increasing the stress on building elements. In addition, moving water tends to cause scour or erosion, undermining buildings and possibly causing collapse. Furthermore, debris carried at high velocity can cause severe damage, and fires can be caused by the collision of fuel containers with buildings.

According to USACE (1988), the faster the velocity of the water is, the greater the damage will be; however, the depth of floodwater is another important factor in determining the amount of damage. This relationship is normally depicted by a depth damage curve such as the example in Figure 2.10

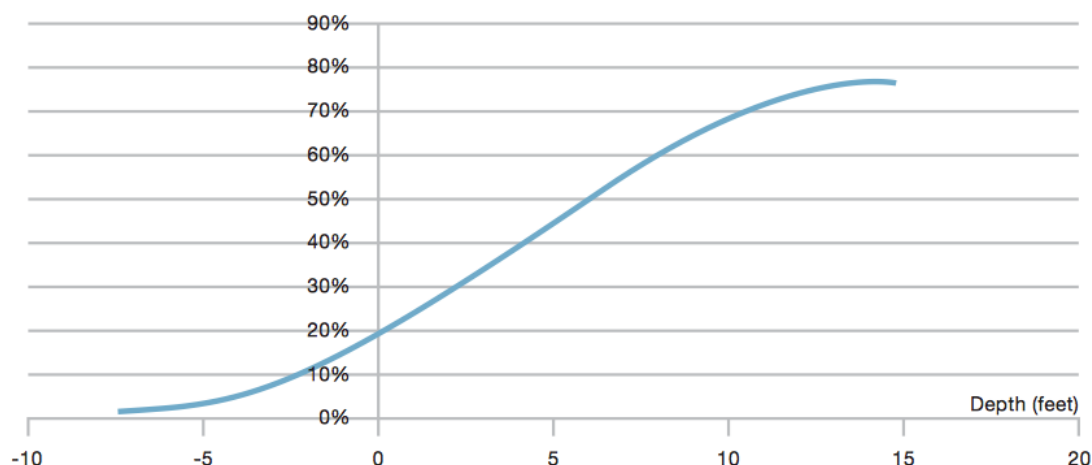


Figure 2.10 Depth damage curve for one story residence with basement. [USACE, 1988]

According to USACE (1988), predicted flood depth is a deciding point for the method of flood protection. As hydrostatic head – the pressure caused by the weight of water being held above the pressure point – will put stresses on walls and will also drive floodwater through walls, if the flood depth is predicted to be greater than 90 cm, flood proofing is not likely to be feasible. The consensus between experts is that the maximum depth acceptable for wet-proof construction should be 60 cm. Also, it has been found that flood depths greater than 60 cm have more capacity to result in structural damage to buildings.

Furthermore, flow velocity is an important factor in the magnitude of flood damage, however, hazard models rarely quantify its impact and its influence is therefore rarely taken into account. A study by Kreibich et al. 2009, examined both water depth and flow velocity and concluded that the latter has a significant influence on structural damage, but minor influence on monetary losses and business interruption. However, it suggests that if water depth is less than two meters then flow velocity alone is not a suitable consideration for estimating monetary loss in flood damage modeling and assessment. The materials used for buildings and the condition of the building can also influence the extent of damage caused. Masonry construction, for example, is able to withstand the impact of floodwaters up to a point but, being a porous material, it will absorb a large volume of water and take considerable time to dry out. Timber construction can be relatively waterproof but is often less robust. Adobe and soil based construction are more vulnerable to scour and erosion. [Jha et al. 2012]

Building quality also has an impact on the ability of a building to withstand flooding. Flash floods in urban environments represent higher risks with respect to damage to

buildings. As mentioned before, high levels of density and congestion characterize many large cities in the world at risk of flooding. Safety standards are also overlooked in many of these cities and as a result a flood in such cities causes high impacts. Floodwaters carry with them the debris of waste and the materials from buildings damaged are also swept along, and in an overcrowded space this may lead to considerable additional damage [Jha et al. 2012]. Therefore, existing buildings located in flood zones are at a particular risk. According to Satterthwaite et al. (2007), regulations should be designed to restrict or prevent new development, although it is possible that new buildings can be designed to withstand the affects of flooding by appropriate use of materials and flood resilient measures

Damage caused to public buildings such as hospitals, clinics, educational buildings, and significant sites such as churches can lead to further indirect impacts like the disruption to education, and a reduction in the capacity for providing both immediate and longer-term health care. Moreover, floodwaters can mix with raw sewage and increase the incidence of water-borne diseases and also the uncontrolled release of various chemicals – some of which may interact with each other – poses a considerable risk to public health [Jha et al. 2012].

National infrastructure is defined as “facilities, systems, sites and networks necessary for the functioning of the country and the delivery of the essential services upon which daily life depends”. These sectors include finance, food, government, emergency services and health. Particularly at risk from flooding, are: communications; transport (roads and bridges, rail, waterborne navigation, both inland and sea, air), telecommunications; energy (power generation and distribution, petrol, gas, diesel and firewood storage and distribution); water supplies, and waste water collection networks and treatment facilities. [CPNI, 2010]

2.13 Indirect impacts of flooding

In addition to the direct impacts of floods, indirect impacts are caused by the interactions within the natural environment and the use of resources in cities and towns. Such indirect impacts can be hard to quantify and value. Some of them will not be fully apparent until after the flooding subsides. [Jha et al., 2012]. Some of these impacts, relevant for the situation of Mexico City, are discussed below.

2.13.1 Natural environment

As high rainfall can cause erosion and landslides, infrastructure can become damaged (especially roads) which are often the only way of accessing communities affected by flooding. The erosion causes concentrations of sediment, which is deposited when the flooding subsides. Furthermore, the smothering of agricultural land by sediment can also be a problem for high value vegetable production, as a large quantity of such sediment is low in organic matter. Therefore, production may never return to its previous level, impacting human livelihoods and nutrition.

Heavy rainfall can also cause damage to vegetation and the ability of vegetation to dissipate the energy of heavy rain may be reduced. Primary forest cover with a high closed canopy is efficient at dissipating rainfall energy while secondary regrowth or trees planted for economic reasons are less likely to have closed canopies and less efficient in diffusing rainfall energy. This can lead to less infiltration to the soil and an increased rainfall runoff, which also further increases the risk of soil erosion and gulying, as illustrated in Figure 2.11



Figure 2.11 A gully caused by soil erosion in Mexico. [Jha et al., 2012]

2.13.2 Human and social impacts

After the floods, survivors have the needs of safe drinking water, food and shelter. They are likely to be traumatized and vulnerable also. In cases where flood warnings and evacuations have been successful, there is a need to deal with the large number of displaced people. As lives saved during the emergency may result in increased hardship and deaths in the aftermath, it is important that flood warnings and preparedness measures are backed up by the stockpiling of immediate requirements (medicine, food, etc). [Jha et al. 2012]

2.13.3 Demographic changes

Flooding can cause significant demographic impacts, causing the age structure of communities to become unbalanced.

A study by Bern et al. 1993 showed that in two cyclone devastated areas in the aftermath of the 1991 Bangladesh cyclone, mortality was greatest in children below the age of 10 and lowest for males greater than age 10. According to this study, affected communities had very few elderly people left alive and they had lost children who were too old to be carried, but not old enough to run inland to the main road, which became the main refuge. More women than men were killed, because they were less physically able to run, but also as they had tried to save their children, putting their own lives at risk. It was also found that more girls and young women were killed than boys because boys were more able to climb trees. These changes in demography varied greatly across the affected areas, reflecting localized flood risk situations. [Jha et al. 2012]

2.13.4 Health impacts

Several studies have found evidence that in some flood events more fatalities have occurred due to water-related disease or injuries, rather than by drowning. A study by Alirol et al. (2010) stated that during the 2007 monsoon floods in Bangladesh, snake bites were estimated to be the second most significant cause of death after drowning and contributed to more deaths than even diarrhea and respiratory diseases

After the flood event, human health is also associated with changes in the balance of the natural environment. For instance, flooding caused by overflow of riverbanks, alters the balance of the natural environment and ecology, allowing vectors of disease and bacteria to flourish. Outbreaks of cholera can result from such alterations. Furthermore, an increase in disease transmission in the post-flood period depends on population

density and displacement, and the extent to which the natural environment has been altered or disrupted.

The provision of adequate non-contaminated water supplies after a flood event is critical. There are often problems due to a lack of fuel to boil water for drinking and the main risks are diarrheal diseases including cholera, dysentery and typhoid. [WHO, 2012]

For example, in a study by Villordon (2014), in Dumaguete City, Philippines, it was stated faecal pollution of water, particularly human faecal sources, are the most relevant source of human illnesses especially during flooding events and rainy season. Exposure and ingestion of faecally-contaminated water and other routes of transmission are responsible for a variety of diseases such as diarrhoea, leptospirosis, and bites from dengue mosquitoes which demands special attention. In addition, diarrhoeal and other waterborne diseases still rank among the leading causes of morbidity worldwide and in the Philippines. According to the World Health Organization (WHO), each year diarrhoea kills around 760,000 children under the age of five and is the second leading cause of death among that age group. Worldwide, there are nearly 1.7 billion cases of diarrhoeal disease every year [WHO, 2013], and based on the surveillance report of 2013 by the Department of Health (DOH) in the Philippines, a total of 1,174 leptospirosis cases were reported nationwide from January 1, 2013 to September 17, 2013. [Villordon, 2014]

Another type of illnesses or diseases caused by flooding are the vector borne diseases, typically transmitted by mosquitoes. These can include malaria, which is caused by a parasitic Protist (a type of microorganism), and Dengue Fever, which is caused by the Dengue virus. Other than vector-borne diseases transmitted by mosquitoes, there are diseases that are borne by other carriers. Leptospirosis (or Weil's Disease) is caused by a bacterial pathogen and transmitted by rodents. The pathogen is excreted into floodwaters. Leptospirosis causes a range of symptoms including fever, headaches and vomiting as well as liver and kidney damage. [WHO, 2012]

Psychological impact on survivors is another significant problem: Many survivors, including children, will be severely traumatized. Several studies have presented a range of symptoms resulting from exposure to natural disasters such as flooding. These consequences include symptoms of post- traumatic stress disorder (PTSD), depression, and anxiety (Mason et al, 2010). Furthermore, Fischer (2005) and Miller (2005) suggested that alcohol consumption, substance abuse, and antisocial behavior increased in the aftermath of the 2004 Indian Ocean Tsunami in India and Sri Lanka.

2.13.5 Human development impacts

Some researchers such as Bartlett (2008) have suggested that severe floods can affect nutrition to the extent that children affected never catch up and are permanently disadvantaged. In addition, births in the immediate aftermath of disasters are likely to result in higher mortality and birth defects, and after a major event, displacement or separation of families due to the death of one or both parents can have long-term effects on the families and the wider community.

2.13.6 Impact on long-term economic growth.

Jha et al. (2012) stated: “In assessing the economic impacts of flooding, care must be taken to adopt both local and national perspectives. Disasters have a large impact on those directly affected but a much smaller effect on the national economy. Some local impacts, such as the effect on the tourist trade, may be balanced by growth in trade elsewhere in the country. Typically, small to medium scale disasters may have no impact on the national balance sheet.”

Studies such as that of Kim (2010), have found that at a national level, there are a variety of relationships between disasters and economic growth. There is some evidence in these studies to suggest that frequent natural disasters can have a positive impact on national economies. The process has been labeled “creative destruction”, and it assumes that reconstruction activities result in increased employment and renewal of facilities. However, Noy (2009) found that the relationship between disasters and economics is influenced by the ability of a country to mobilize resources for reconstruction. Therefore, developing countries are unlikely to benefit in the long term from disasters. Loayza et al (2009) found that median level flood events had a considerably positive effect on economic growth, while larger scale floods had a small effect.

2.13.7 Impact on development goals

As a result of the lack of insurance cover, some countries divert funds from other development goals to flood recovery operations after the event. Some governments have faced liquidity problems to face massive natural disasters and have to depend on international aid, development funds or insurance to reinforce national tax revenue. Therefore, economic priorities have to be set against a background of widespread need, and the challenge is for governments and the private sector to work together to set the priorities for reconstruction.

Another post-flood impact, which affects the people, is the burden of debt for restoration of the economy, which puts additional pressure on people and reduces their financial ability to cope with the changed situation. [Jha et al. 2012]

2.13.8 Impact on livelihoods

Livelihoods are usually undermined in severe flood events. The severity of this is a function of the impact of the flood on employment availability, specifically whether any members of the household have been killed or injured and the degree to which they contributed to the social and economic functioning of the household. [Jha, 2010] At the community level, the skills that will be in demand suddenly (like those required for building replacement infrastructure) could be beyond the available within the surviving population.

2.13.9 Business interruption

Some businesses fail after the flood event due to direct damage, or to indirect impacts such as business interruption. Businesses may have to close due to lack of access or failure of services, such as water supply, wastewater collection and treatment, electricity, roads and telecommunications. This will likely have economic implications for areas related economically to the immediate flooded area and the replacement of such services can be complex, will take time and money, and cause serious economic losses. Businesses that are able to continue operations could take months to recover and to return to normal trading. The recovery process may be delayed further by the loss of documentation in the flooding, leading to delays in tracing orders, completing insurance claims and issuing invoices. In addition, other indirect effects include an increase in expenses, a lack of demand, and a short-term loss of market share, loss of key personnel, lack of available staff, loss of production efficiency, and loss of supplies. [Jha et al. 2012]. A study by Wenk (2004) found that; for many businesses, these impacts can be catastrophic: as 43% of companies experiencing a disaster never reopen and 29% of the remainder close within two years.

2.14 Assessment and prioritization of needs

As shown in Table 2.6, there are different types of assessments, which may be carried out in the aftermath of a flood. These assessments have different purposes and can be carried out with varying degrees of accuracy. A rapid assessment is required at the outset of recovery, to assess the level of damage and the priority areas for direction of recovery effort.

Type	Definition
Damage Assessment	An assessment of the total or partial destruction of physical assets, both physical units and replacements costs
Loss Assessment	An analysis of the changes in economic flows that occur after a flood and over time, valued at current prices
Needs Assessment	An assessment of the financial, technical and human resources needed to implement recovery, reconstruction and risk management. Usually 'nets out' resources available to respond to disaster.
Rights-based assessment	An assessment that evaluates whether people's basic rights are being met. Has its origins in the United Nations Universal Declaration of Human Rights
Rapid Assessment	An assessment conducted soon after a major flood event, usually within the first two weeks. May be preceded by an initial assessment. May be multi-sectoral or sector-specific. Provides immediate information on needs, possible intervention types and resource requirements
Detailed Assessment	An assessment undertaken after the first month to gather more reliable information for project planning. Often takes about a month to conduct and is usually sector-specific.
Housing Damage Assessment	A damage assessment that analyzes the impact of the flood on residential communities, living quarters and land used for housing.
Housing sector assessment	An assessment of the policy framework for housing, the post flood housing assistance strategy and the capability of the housing sectors to carry it out
Community-based assessment (CBA)	An assessment that analyses how the context will affect reconstruction and the way in which communication with the affected community can support the reconstruction effort. It includes government and political risk analysis, stakeholder analysis; media communication environment and local capacity analysis and social and participatory communication analysis

Table 2.6 Types of assessments after a flood. [Jha, 2010]

Jha et al. (2012), recommends that in any assessment and priority setting exercise it is important to consider the needs of the vulnerable. Good practice includes the collection of information on the needs of members of vulnerable groups.

2.15 Mitigating damages

There are steps that can be taken after a flood, by both governments and individuals, which may reduce the level of damage. Where floods are prolonged, the potential for water-borne disease is greater, materials in contact with floodwater will degrade and the potential for scour, erosion and undermining increases. For these reasons, draining

floodwaters from the affected area can be a first step in recovery. In addition, hard engineered flood defenses have the disadvantage that, if overtopped, they stand in the way of water regaining its normal course and lead to more prolonged flooding. Therefore, either pumping out the water or, possibly, destruction of portions of defenses is recommended. Regarding buildings and enclosed areas, underground spaces allow water to accumulate and in some cases this can increase structural damage, if the water outside has receded. Therefore, careful pumping out of water from such areas is advisable.

Secondary damage is also possible, either from wet and damaged contents, or from ill-advised attempts to dry buildings and contents. It is advisable to remove wet and damaged contents from buildings as soon as possible, as this will enhance drying and reduce damage. Furthermore, in temperate conditions, the access of air to wet buildings and contents will enhance drying and speed up recovery. [Jha et al. 2012]

2.15.1 Structural measures to prevent or reduce floods

These actions include the construction of works that directly interfere with rainwater or the draining through the rivers, to prevent its passage, confine it, manage it, store it or change its speed and flow.

The works commonly built to reduce flooding caused by the overflowing of rivers, are:

- Perimeter barriers along populations or important buildings
- Longitudinal barriers along one or both sides of a river.
- Longitudinal walls along one or both sides of the river.
- Permanent traps through floodways or channeling structures, in which the water is directed into other channels, lagoons, the coast or directly to the sea and not returned to the river.
- Temporary diversions to gaps or low areas of the floodplain. The water returns to the river when lower discharges are present.
- Cut of streams or corrections to increase the slope of the river and therefore its capacity hydraulic line.
- Dams storage, which can be one or more staggered.
- Dams breaks peaks, usually built several staggered.
- Dams to retain silt, which do not affect the hydrographs but avoid siltation of other channels and therefore the hydraulic capacity.

- Channeling or piping of a channel, are used in sections where streams or rivers cross towns or cities. They should be built with additional capacity to absorb peaks, or designed in conjunction with permanent diversion structures.

Normally, all sections of all streams reach a certain degree of balance, which means that, if not changed artificially, the water and sediment will continue draining as they are doing. Conversely, if modified naturally or artificially, some parameters will over time slowly change the river reach to a new equilibrium condition. Therefore, it should be emphasized that the presence of a structure in the riverbed, alters and modifies its runoff and hence the equilibrium or natural process that is subject to. Alterations produced in the flow of a river immediately translate into erosions or deposits on the stream, which can be very local or cover large stretches of the river.

It can be said that there is a balance between the flow, the solid amounts entering the stretch under, the material characteristics, the longitudinal slope of the river and the geometry of the cross section.

A modification to any of these parameters, influence the others and leads to a new equilibrium state. Modifications may be slow or rapid, natural or man made. The most common causes of sudden change are due to:

- Changes in the river due to cuts in streams.
- Earthquakes change the terrain and river tracing.

Modifications that man produces on channels and change its natural equilibrium condition can be beneficial or harmful to the future behavior of the river. Furthermore, the same action can be beneficial to a river and damaging to another. Among the most important alterations due to the human factor are noted:

- Construction of dams. These works originate alterations of importance, both upstream and downstream of the dam. First, they change the annual hydrograph and sometimes the volume of annual runoff; and second, they interrupt the transport of sediments and therefore the slope of the river is modified in the section downstream of the dam;
- Watershed Erosion mainly from deforestation and poor farming techniques. The main effect of these actions is the increased production of solid material to be deposited in the riverbed reducing its capacity.

There are other human activities that also affect the channels but with an order of magnitude smaller than the two aforementioned, among them may be mentioned:

- Construction of facilities for navigation.
- Decrease the width of rivers.
- Correction of channels.
- Piping or tubing runway.
- Construction of diversion dams.
- Construction of roads, including bridges and culverts.
- Permanent traps through floodways.
- Temporary diversions to gaps or low areas.
- Removal of vegetation.
- Dredge of the main channel and demolition of obstacles.

When a dam is built, stagnation originates and the transported sediments perform according to the following mechanism: when currents enter the reservoir, the bulk material is deposited according to the decreasing water velocity due to the extension of the stream, forming an accumulation of coarse sediment called delta and a change in the slope of the river in the first section upstream of the reservoir; the finer sediment will continue in ward of the reservoir as a density current, later it will stop, and settle on the bottom. (See figure below)

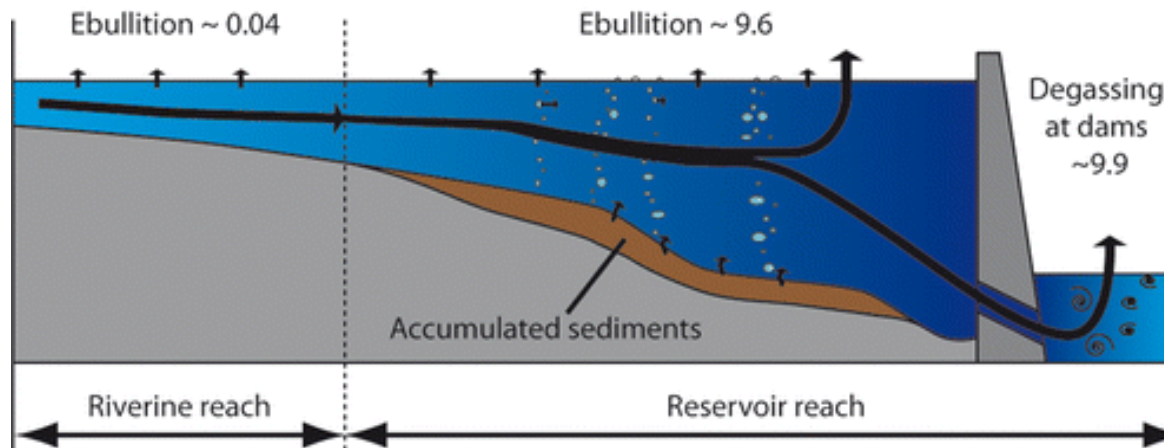


Figure 2.12 Accumulation of sediments in dams. [Maeck et. Al, 2013]

There are reservoirs where no such current is formed; and in the reservoir or in large part thereof, a generalized turbidity will occur and evolve according to the particular dynamics of storage [CNA, 2011]. These include the construction of works that directly interfere with rainwater or the draining through the rivers, to prevent its passage, confine it, manage it, store it or change its speed and flow. The works commonly built to reduce flooding caused by the overflowing of rivers, are:

- Perimeter barriers along populations or important buildings
- Longitudinal barriers along one or both sides of a river.
- Longitudinal walls along one or both sides of the river.
- Permanent traps through floodways or channeling structures, in which the water is directed into other channels, lagoons, the coast or directly to the sea and not returned to the river.
- Temporary diversions to gaps or low areas of the floodplain. The water returns to the river when lower discharges are present.
- Cut of streams or corrections to increase the slope of the river and therefore its capacity hydraulic line.
- Dams storage, which can be one or more staggered.
- Dams breaks peaks, usually built several staggered.
- Dams to retain silt, which do not affect the hydrographs but avoid siltation of other channels and therefore the hydraulic capacity.
- Channeling or piping of a channel, are used in sections where streams or rivers cross-towns or cities. They should be built with additional capacity to absorb peaks, or designed in conjunction with permanent diversion structures.

Even when a nation develops a tightly integrated infrastructure, the failure of one element can lead to a domino effect of further indirect consequences. For example, the failure of electricity systems can lead to pumping station failures, which could worsen both the depth and impact of a flood event. In addition, road failure leads to the inability of emergency responders to reach affected populations. [CNA, 2011].

Therefore, planned redundancy is an idea developed to increase the capacity of systems so that even if a proportion of the infrastructure is affected, the extra demand can still be absorbed elsewhere. In power generation grids this could be achieved by having reserve capacity in the system. [CNA, 2011].

2.15.2 Non-structural flood mitigation measures

Flood warnings are arguably the most fundamental mechanism for flood risk management, since even where structural flood defenses are provided, residual risks remain. Therefore, a flood risk management strategy that uses flood warnings, either solely or in conjunction with other management options can help make the occupation of floodplains and coastal flood risk zones more sustainable over time [Messner et.al, 2007].

Flood warning systems are one part of a larger system known as flood forecasting, warning and response. The performance of flood warnings depends greatly upon floods being detected. Warnings systems may under-perform, or indeed fail, if flood detection and/or flood forecasting is flawed somehow.

Growth of population in high-risk areas and insufficient application of building codes, are the principal reasons for the increase of losses from natural disasters in recent years. Kunreuther (1994) examined why homeowners commonly do not adopt cost-effective protective measures or purchase insurance, even when studies of the added costs of materials and labor for hurricane-resistant designs indicate that it will add 4-5% to the cost of a new home and that this additional expense is not significant relative to the added benefits of safety and security.

According to the author, individuals might perceive a sufficiently low probability of a disaster causing damage to their home such that the investment in the protective measure will not be justified; a key question is "What is the maximum amount that a person would be willing to pay for protection?" If property owners concentrate on the expected benefits from the mitigation measure during the time they plan to live in the structure, then the WTP depends on the amount of the loss reduction and the anticipated length of stay in the home.

One of the arguments used to explain why individuals do not adopt protective measures is that they assume substantial assistance from the government will be available if they suffer losses from a disaster. However, there does not appear to be any evidence to demonstrate this is true. The two principal reasons given in this study as to why private insurers do not offer policies to cover water damage from hurricanes and floods are the uncertainty of the risk and a fear of the severe financial cost of a catastrophic disaster.

Frequent disasters, such as fire, make it possible to evaluate such risks accurately. Events of low probability and high consequences such as hurricanes, floods, and earthquakes; present more problems because of the relatively limited past data available, and therefore, insurers rely on risk assessments carried out by meteorologists, hydrologists, and seismologists, and such studies carry uncertainty and ambiguity with respect to the chances of a particular disaster occurring in a specific area. [Kunreuther, 1994]

The challenge is how to promote investments in loss reduction instruments, while placing the weight of recovery on those who suffer damages from natural disasters. Theoretically, insurance is an effective policy tool for achieving both objectives, because

it rewards investments in cost-effective mitigation measures with lower premiums. In practice, however, insurers do not charge premiums that encourage loss prevention actions. It is believed that few people would adopt these measures based on the small annual premium reduction, as compared to the upfront cost.

One way to promote the acceptance of cost-effective loss reduction measures is to have countries include them into their building codes and give each building that meets or surpasses these standards a seal of approval. To strengthen this procedure, financial institutions could require an inspection and certification of the facility as a condition for obtaining a mortgage, and insurers should reward well-designed buildings with lower premiums. [Kunreuther, 1994]

Furthermore, modern communications developments in flood control have become accessible, such as modern forecasting and early warning systems as well as remote sensing and the technology for converting forecasts from mathematical models of meteorological weather situations into warning systems. [Plate, 2002].

A flood-forecasting model was implemented in Germany in 1995 to avoid flooding of cities on the lower end of the River Lenne, the main tributary of the Ruhr River. An on-line flood forecasting model was developed based on a distributed deterministic catchment model. From the application of this model, strategies for the operation of the Bigge Reservoir during floods derived. [Goppert et al, 1998]. However, according to Ferraris et al (2002), warning systems based on rainfall observations and rainfall–runoff modeling do not provide opportune predictions required to implement the required precautionary civil protection measures. Social safety demands that hydrologists predict ground effects 24 hours in advance.

In a study by Werner et al (2005); a European Flood Forecasting System (EFFS) developed to deliver flood warnings at lead times of between 5 and 10 days was described.

Furthermore, in recent years, flood forecasting systems have been gradually moving towards the adoption of ensembles of numerical weather predictions (NWP), known as ensemble prediction systems (EPS), to produce their predictions. In a 2009 study the scientific reasons of this change towards such ‘ensemble flood forecasting’ was reviewed and several issues related to best practice in using EPS in flood forecasting systems were discussed [Cloke and Pappenberger, 2009]. However, flood forecasting and warning is only one aspect of the application of communication technology, as it

also allows the dynamic operation of flood control systems. A reservoir for flood control, for example, can be controlled based on forecasting results to provide optimal protection by eliminating the peak of the flood wave. In other cases, a series of barrages can be operated through remote control to provide maximum storage of floodwaters in the retention space of the barrage system [Plate, 2002].

2.15.3 Impact of river control structures

Normally, all sections of all streams reach a certain degree of balance, which means that, if not changed artificially, the water and sediment will continue draining as they are doing. Conversely, if modified naturally or artificially, some parameters will over time slowly change the river reach to a new equilibrium condition. Therefore, it should be emphasized that the presence of a structure in the riverbed, alters and modifies its runoff and hence the equilibrium or natural process that is subject to. Alterations produced in the flow of a river immediately translate into erosions or deposits on the stream, which can be very local or cover large stretches of the river.

It can be said that there is a balance between the flow, the solid amounts entering the stretch, the material characteristics, the longitudinal slope of the river and the geometry of the cross section. [CNA, 2011].

A modification to any of these parameters, influence the others and leads to a new equilibrium state. Modifications may be slow or rapid, natural or man made.

Furthermore, in plains is where there is a greater potential for economic development, however, most of these are prone to flooding, therefore, these areas require more structures for protection, as much as the development justify these. The structures for flood control are built in the channels or basins to guide, lead, confine, hold or store the runoff. With them the maximum flows are reduced, they facilitate the free passage of water; and protect populations and extensive areas from the effect of runoff. The various studies and flood control methods involve:

- Control measures in watersheds to reduce runoff and minimize the costs of flooding.
- The holding capacity storage or flood channel capacity.
- Deviations, with channels to other areas.
- Confinement of flooding in a certain area; known as temporary flooding.

Normally, the economic life of a projection measure is selected as the useful life; since its cost is compared with the benefits it will bring over a period of time, regardless of

whether the structure can last longer. Among the factors to consider in selecting the type of measure to be done are:

- The Consequences of failure of the measure, especially in loss of life.
- The real life expectancy of the measure and not only economic life.
- The cost of increased security.
- Economic availability.

Also, to know the levels reached by the water at any point of the study area and at any time during the passage of an avenue, a physical or mathematical model is used to analyze the flow of the avenue along the stretch of the river under study and its respective plain. [CNA, 2011].

2.15.4 Examples of mitigating measures in Mexico.

The main causes of the impacts of flood damage in Mexico according to the National Water Commission (CNA) are:

- Lack of infrastructure.
- Weakness of state agencies to exercise police power.
- Indifference of the population.

In Mexico, the illegal occupation of the federal land in several states of the country is constant (Figure 2.13).

So in the rainy season, settlements built on low ground are flooded, and desperate actions are carried out to mitigate their effects. Therefore, interim defenses have been frequently built; but some are abandoned after the flood event and destroyed due to lack of maintenance; so in the next flood, the works start over [CNA, 2012]. On the other hand, there are no programs for relocation or refurbishment of houses. Furthermore, some developers occupy federal or private land, they settle in low places, and some receive "preferential treatment", and this has major economic benefits for some construction companies. Some constructions are done in low areas authorized by the municipalities [CNA, 2012].



Figure 2.13 Irregular occupation of federal land in Mexico City. [Milenio, 2016]

Another problem is the construction of levees, which offer a false security, as there is danger of massive flooding if they collapse.

However, there are virtually no cases in which it is possible to solve flooding problems permanently. Some of the most important reasons that do not allow the solution are the cost of the structures, conflicts of interest involving land use, and poor economic feasibility of such projects.

Regarding the cost of construction of structures, it is based on the frequency of flooding. In the protection of farmland, for example, the design flood frequency can be between 5-25 years because major events may require works worth more crops to be protected. In other cases, where flooding can cause loss of life it may be preferable to install warning systems or relocate the population that is at risk, rather than projecting works for frequencies of occurrence of 10,000 years. Also, the results of the hydraulic and geomorphic studies provide forecasts on future developments and current estimates of magnitudes of the mean, minimum and increasing flow rates, the minimum levels, maximum and average, the potential flood zones, flow rates, and transport capacity [CNA, 2011].

The most common structures in natural currents are:

- Works for torrential transverse control. They operate like small weir dams.

- Braker walls for diversion of flow lines.
- Braker walls to promote sedimentation processes.
- Works built to harness a natural flow to a passage structure, e.g. a bridge, culvert, sewer, among others.
- Longitudinal bank protection works against scour.
- Flood protection. They are works that control the maximum expected level within the floodplain.

Learning to live with floods means not only to have ways and means of exit when they occur, but also to take advantage of the good they bring, and learning from them. This is, ultimately, the knowledge accumulated over generations by people living outside the major rivers of a country and the reason why many people changed their way of life.

After the floods, the land is more fertile, pastures are more succulent and water is more abundant; people know and therefore prefer to risk losing everything occasionally instead of having the agricultural yields reduced and a lifetime living in remote areas of rivers.

Flooding of the Nile, for instance, was considered the blessing of the gods, who fertilized their seeds buried in the muddy land and developed commercial activity between Upper and Lower Egypt, and between them and the peoples of then Mesopotamia. Herodotus, the Greek historian, said that Egypt was a gift of the Nile. But not only did the Egyptians knew how to take advantage of floods for agriculture, also they measured and allocated land across for farming families. It was due to the planning of land use after the floods and the need for rapid measurement of fields and their division between farmers that the rope of thirteen sections and twelve knots was invented, which transformed the circular sections into straight angles, allowing a better space utilization, in what later came to be transformed into the famous Pythagorean Theorem. [CNA, 2011].

The complexity of the design and management of systems of irrigation canals and the division of land, not only contributed to the development of geometry, but also the techniques of utilizing materials that were applied in the construction of the seven world wonders. Therefore, living with floods means, besides of making the most of the elements of nature to achieve development, to also produce new scientific knowledge that can be applied for other purposes, in other circumstances and places.

For this, the strategies to follow are:

- Assume the reality of the region.

- Prepare the population for adversity.
- Do not alter the physical environment as this turn against man. •
- Do not fight the river, but know its effects
- Prevent the negative action of the river as it grows.
- Construction of lake dwellings.
- Laws that include the relocation of families at risk of flooding.
- That the population with flooding problems should be aware of the risk to which it is exposed and be prepared to face it, one of which is: have some means to move (boats), having rescuers, know the minimum standards of rescue.
- Drills coordinated by Civil Protection.
- Campaigns in radio, TV and newspapers.

In a particular way, the cheaper alternative that can help flood control projects is to live with recurrent flooding, assume the reality of recurring floods in the region and prepare the population for temporary adversity, besides to not alter in the physical environment which can generate more complex problems to solve. Consideration should also be given to moving (temporary and / or permanent) of families at risk of flooding. Figures 2.14 and 2.15 show houses built in flood plains.



Figure 2.14. An example of how some houses have been built in low laying flood plains. [CNA, 2011].



Figure 2.15 An example of how to build houses in flood plains in medium altitude areas. [CNA, 2011].

2.15.5 Case of the Gaviotas Sur neighborhood, Villahermosa, Mexico.

The neighborhood of Las Gaviotas was in 1980 a low-income neighborhood located on the right bank of the river Grijalva, on the opposite side to the city of Villahermosa (see figure below).



Figure 2.16 Gaviotas Sur neighborhood in the city of Villahermosa. [Wikimapia, 2013]

Most of the houses were built of tree trunks or palm-roofed palapa and had minimal furniture, usually a grill, a table, chairs, and instead of beds, sunbeds. Hardly there were houses with a cement floor as it usually was dirt. Because of its location, residents were

aware that every year the river rose enough to exceed the small board that protected and caused a "light flood" (about 20 cm on average).

The inhabitants knew that living away from flood, meant having to walk half an hour or an additional hour to reach their workplaces, which otherwise were five minutes across the river in collective boat. Additionally, the search for land in "no flood" area, involved time because there were not many dry lands and resources to buy the land and for the subsequent construction of housing. On the other hand, the people knew long ago that the flood lasted on average about two or three weeks. So in a rapid assessment, it can be seen that there are positive and negative factors to this:

- Positive factors:
 - Houses of little commercial value, easily repairable, few household goods, and proximity to the workplace.
- Negative factors:
 - Few sites for relocation, remoteness of the workplace, additional time to transport, overcoming the flooding time.

Taking these factors into account, the less aggressive solution is to stay in place and not seek alternative sites for new housing, even when they had to withstand flooding during the time it lasted. Although it seems hard to believe, the people of Las Gaviotas, chose the option to withstand flooding and take life as in harmony with the flood, so to avoid major inconvenience. The actions for living with floods consisted on placing bricks at the base of furniture to lift them gradually as the flood grew and hang the hammocks in higher brackets. When the water level comes down, the reverse operation is made, until the water level is back to normal. [CNA, 2011]

In Mexico, other examples show how man can harness the knowledge on the occurrence of discharges to exploit efficiently the floodplains available in cities.

For instance, the Santa Catarina River; which crosses the city of Monterrey in Northern Mexico from West to East, usually takes a minimum flow of water throughout the dry season and only during the rainy months it increases runoff. To take advantage of the large excess surface of the river, a channel was built which covers a quarter of the total width of the river and the remaining three quarters has a plain where sports fields are conditioned, and a site where transient events like circuses are installed, among others. [CNA, 2011]

Authorities in Monterrey are all aware that at some point the river can increase the level and destroy everything that has been built there, but it is known that the frequency of such a flood, makes the cost of the damage to be absorbed by the cost of having to build all these buildings in more remote and dispersed locations; (see picture 2.17)



Figure 2.17 Sports fields in the floodplain of the Santa Catarina River in Monterrey, Mexico [CNA, 2011]

A similar case happens in the city of Torreon Coahuila, which is also partially crossed by the Nazas River, which also forms the border between the states of Coahuila and Durango. Here the river contains recreational buildings and roads that work most of the time since the Nazas River is controlled by upstream dams El Palmito and The Doves [CNA, 2011]. Several times it has happened that increases in the level of the river has caused the roads to be closed to vehicle traffic and cleaning and repair after floods was required, but that represents a lower cost than finding other space within the city for roads.

A third example is the city of San Luis Potosi, which is crossed by the Santiago river (Figure 2.18) where roads are closed to traffic when a flood occurs and re-open once it has passed, taking also an attractive urban image; (see figure 2.19).

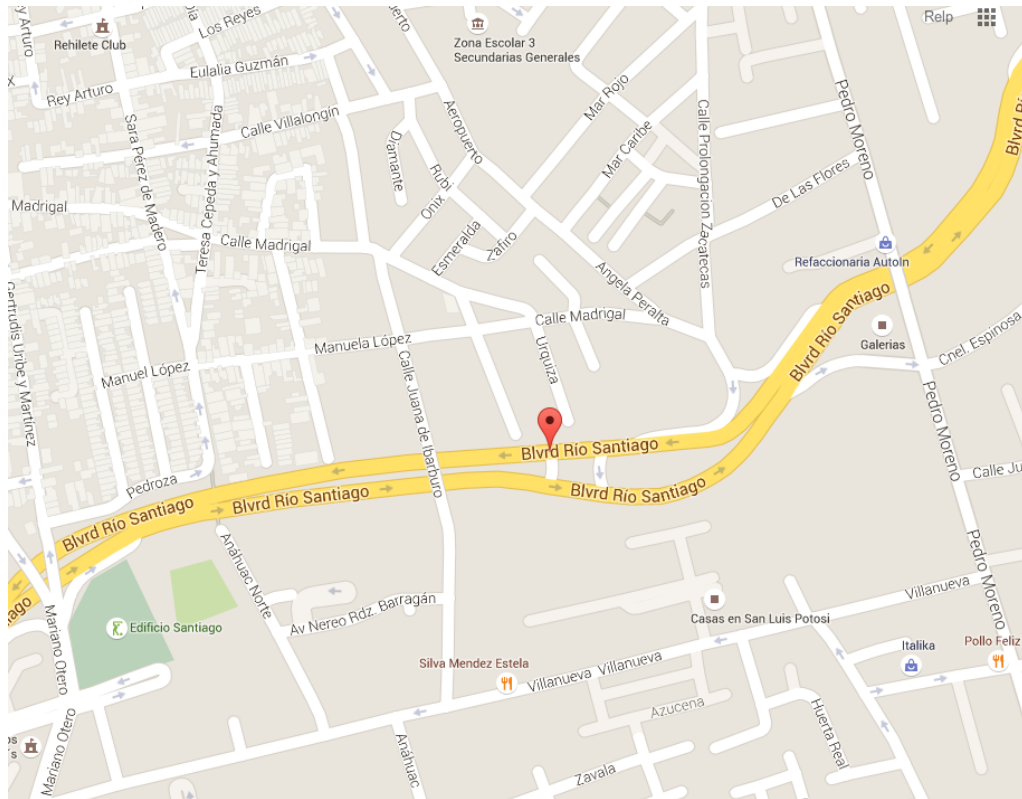


Figure 2.18 Map of the City of San Luis Potosi and River Santiago Blvd. [Google, INEGI, 2016]

Note that the road has respected the hydraulic area. In this view, the road was closed due to the start of a flood. In general, these are just some examples of the coexistence of man with flooding.



Figure 2.19. Boulevard on the river Santiago. [CNA, 2011]

2.15.6 Proposal of alternatives

According to CNA (2011) the motivation to determine an action by decision makers frequently is a result of the proposal of a company, academic institution, etc; that offer a "solution" to the problem of flooding that presents the area. Therefore, if the proposal is for a construction company, the offer will be to build a civil work such as a dam or levee; if the proposal is by company specializing in dredging, the offer will obviously involve dredging of the sediment in the channel to increase the capacity thereof; if the proposal comes from an academic institution, it will surely include the installation of an early warning system; just to mention some examples. [CNA, 2011]

This process must be reversed: first identify the problem, then study site conditions and just then raise a number of alternatives that, by themselves, or wise combinations of them can solve the problem.

- To this point, the following must be known:
- The topographical conditions of the areas at risk and around it to implement any of the possible alternatives. This, of course, must include the "floodplain" which is nothing but the natural extension of the stream to handle extreme discharges, and this generally with higher vertical resolution than the rest of the area of interest,
- Conditions for the development of the area, city maps, population statistics, paths and roads, critical infrastructure such as schools, hospitals, among others,
- The geometry of sufficient cross sections of the riverbed,
- The definition of the return period for which alternative flood control measures will be designed. The return period is decided based on the risk to human life, the economic value of goods that may be damaged, among other reasons. The flow rate corresponding to the return period is obtained from the data, and studies, whether meteorological and / or hydrological.
- Flow in the section of interest,
- The areas to be flooded for that design flow and the water depths over these areas.

In general, a flood control program is an integration of several of the alternatives to produce the lowest cost or the best benefit to cost, based on the comparative study of the various alternatives. [CNA, 2011]

In general, the various alternative measures for flood control can be classified into two broad categories:

- Structural measures.
- Non-structural measures.

Structural measures are associated with works (in the field of civil engineering) that allow the design flow to be driven through the study area without causing flooding and can manifest in many different ways. Non-structural measures are associated with no attempt to changing the capacity of the channel through civil works, but instead minimize harm to the population (in their lives, possessions or activities) through other means. [CNA, 2011]

It is possible that some of these non-structural measures involve a certain amount of civil work, but rather as an accessory, not as the control mechanism itself. For example, the establishment of an early warning system may require the construction of houses for the installation of rain gauges and telemetry limnigraphs in the basin upstream of the area concerned, but still considered a non-structural extent that it does not attempt to modify the flow conditions on the stream, but increase the information on it.

Chapter 3. MEXICO CITY CATCHMENT AND FLOOD PROCESSES

Summary

Mexico City is located in the Southern part of the Basin of Mexico, an extensive high mountain valley at approximately 2,200 meters above sea level and surrounded by mountains reaching over 5,000 meters above sea level. This valley is commonly referred to as the Valley of Mexico. Every year, Mexico City is affected by severe flooding events, which are affecting deeply the urban environment and the 20 million inhabitants. This situation is becoming more and more serious and represents a major risk for the population. The situation is the result of a complex process that combines hydrological characteristics and urban development. This chapter describes in detail the processes influencing flooding in the city, and cites all the recent studies about the hydrology of the catchment and the types of flood problems occurring frequently, as well as recent actions to overcome these issues.

3.1 Mexico City catchment

3.1.1 General

The Mexico City catchment was originally an endoreic basin and the only way of runoff evacuation were through evaporation. After a series of large floods, which occurred in 1604, it was decided to build an artificial outlet for the basin, and the idea to construct a canal was conceived. Before the canal works were finished, several flood events occurred, especially between 1629-1635, when an estimated total of 30,000 people died and a similar number left the City. After this event, the idea to relocate the city was explored.

The contruction of the channel outlet of the basin was begun until 1866. It was designed as a channel of 39.5 km, which began on Lake Texcoco and ended in Tequixquiac tunnel, at nearly 10 km of length. The work was the second artificial outlet for draining

the Valley of Mexico and was completed in 1900, which was thought to be a definitive solution to the flooding of the city, which in those years was inhabited by under a million people. (Figure 3.1)

The system worked fairly well until 1925, year in which large-scale flooding occurred again. At that time it was found for the first time that differential subsidence affected the collector system.

The population growth was exponential from 1930, when it is estimated that the city was inhabited by a million people, which increased to two million in 1940, to three in 1950 and five in 1960. In those years, thousands of miles of canals for drainage were built and the construction of the dam system for the regulation of floods in the west of the city began. Furthermore, from 1930 to 1960 thousands of kilometers of drainage ducts were constructed as well as a system of dams to regulate the discharges in the west of the City. In addition, several pumping stations were installed with a cumulative capacity of more than 100 m³/s and the rivers crossing the City were enclosed in ducts to avoid flooding. For example, the Mixcoac, Piedad and Magdalena rivers, which drain the catchment in a direction predominantly from West to East, are first intercepted by the drain system by gravity and after by the great channel through the use of pumps. [CNA, 2011]. Despite the work done in those years, between 1941 and 1951 recurrent and increasing flooding occurred. In 1950, the newspaper 'El Universal' wrote that two-thirds of Mexico City was flooded with water and mud and five people died.

The solutions carried out included the construction of large pumping stations in the main collectors of the Grand Canal and the substantial increase in the capacity of this, by extending it and constructing the second tunnel of Tequixquiac, completed in 1954.

Between 1954 and 1967 thousands of kilometers of collectors were built, and pumping plants with a cumulative capacity of over 100 m³/s, an interceptor in the West, the piping of the rivers La Piedad, Consulado, etc.; but these works continued to be inadequate by the rapid growth of the urban area and, above all, by the sinking of the city. [CNA, 2011] The deep drainage system was a solution initiated in 1967. This work consisted in two receptors of 5 m in diameter and 18 km in combined length, with a depth varying from 30-50 m. This work, considered by many as "definitive", opened in 1975. [Dominguez, 2000]

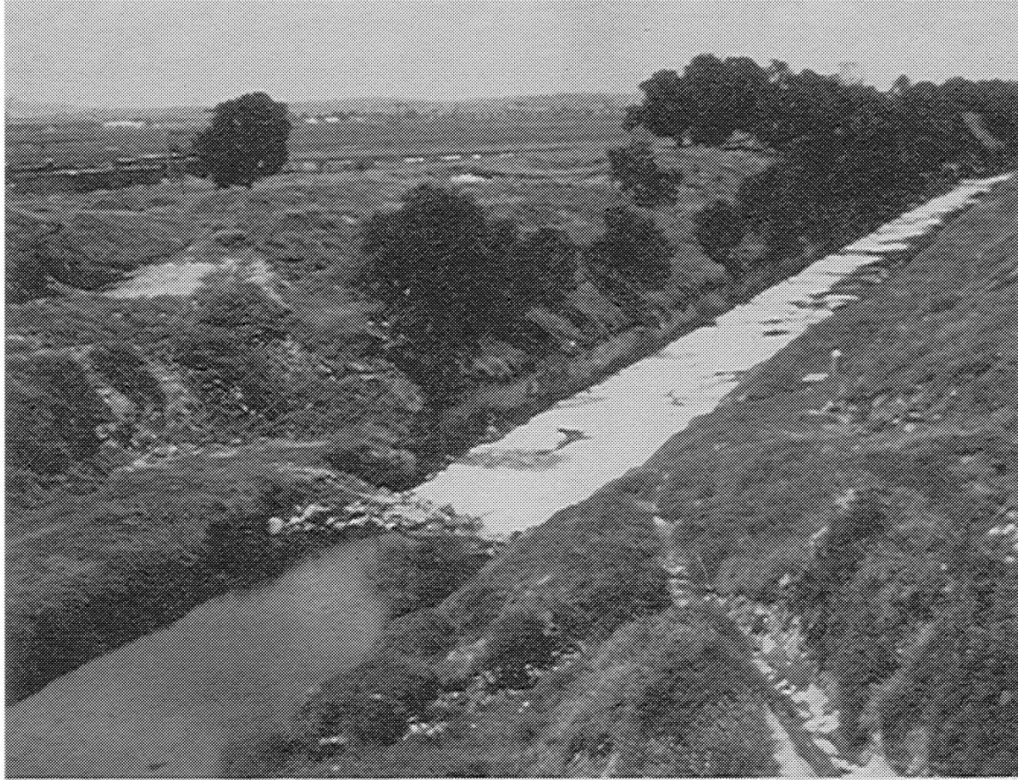


Figure 3.1 A view of the Grand Drainage Canal (Gran Canal Desague), which carries wastewater and stormwater runoff from the Mexico City Metropolitan Area. The canal exits the Basin of Mexico through the Tequisquiac tunnel and empties into the Moctezuma River, a tributary to the Panuco River, which flows into the Gulf of Mexico. [Luege, 2012]

3.1.2 Water supply in Mexico City

As mentioned above, attempts to control flooding and provide water and wastewater services in the metropolitan area of Mexico City have included massive engineering projects, such as a deep drainage system and the importation of water from the Cutzamala Basin. The prevailing conception among the population has been that water resources are state property and, therefore, their use is a constitutional right (though not identified as such in the constitution) and free of charge. Traditionally, water supply and drainage services have been strongly subsidized by the federal government for decades.

The results of this, for several decades, were financial deficits and waste of the resource through leakage and inefficiency of use. Quick urban growth and insufficient finances have restricted the capacity to satisfy demands, extend the distribution system to areas with poor service, and provide adequate wastewater treatment prior to disposal. [CNA, 2011]

In 1988, Mexico initiated reforms in water resource allocation and water services, and the case of Mexico City can be considered as an extreme scenario that could be faced in many other cities. Because of the complexity of the problem and its relevance to other cities in the world, a binational study was undertaken by the Mexico Academy of Science (Academia de la Investigación Científica, A.C.), the Mexico National Academy of Engineering (Academia Nacional de Ingeniería, A.C.), the National Research Council of the U.S. National Academy of Sciences and the U.S. National Academy of Engineering. The study published in 1995 was part of a non-governmental partnership to sustain and strengthen science and technology in both countries through collaborative activities. [NAS, 1995]

A planning group of representatives from the various academies met and concluded that a study of the Mexico City aquifer would be an important undertaking. The study scope was broadened to include the technical, social, economic, and institutional aspects of water service. In January 1992, a binational, multidisciplinary committee of volunteer experts was appointed by the academies of the United States and Mexico. The study was implemented with financial assistance from the Ford Foundation, Tinker Foundation, U.S. Environmental Protection Agency, United Nations Development Program, Mexico National Science Foundation (Consejo Nacional de Ciencia y Tecnología), Mexico Ministry of Health (Secretaría de Salud), and U.S. National Research Council. [NAS,1995]. Exhaustive investigations were conducted as well as deliberations over a 30-month period, and, according to the authors, the integration of information on water supply, distribution, drainage, quality, flooding and institutions was no easy task in the case of Mexico, as the data collected by federal, state, and local authorities for water management and planning were disparate, not in a published form and not collectively integrated or analyzed by the scientific community. [NAS, 1995]

3.1.3 Description of the Mexico City aquifer and its exploitation

The Basin of Mexico is located in the central part of the Trans-Mexican Volcanic Belt and has an approximate area of 9,000 square kilometers. The basin, at an altitude of 2,200 meters above sea level, is the highest valley in the region, and is surrounded by mountains that reach elevations of over 5,000 meters above sea level. Average annual temperature is 15 degrees centigrade (or about 60 degrees fahrenheit). Most of the 700 millimeters of annual rainfall is concentrated in severe storms from June through September. [NAS, 1995]. The basin is a naturally closed depression that was artificially opened in the late 1700s to control urban flooding. Sources of ground water recharge in the basin are largely derived from infiltrated precipitation and snow melt in the

surrounding mountains and foothills, which move as subsurface flow toward the lower elevations. In its natural state, the basin contained a series of lakes, ranging from fresh water lakes at the upper end to those at the lower end where salt is concentrated due to evaporation. The ground water flow produced numerous springs in the foothills and upwellings in the valley (Figure 3.2 illustrate this process).

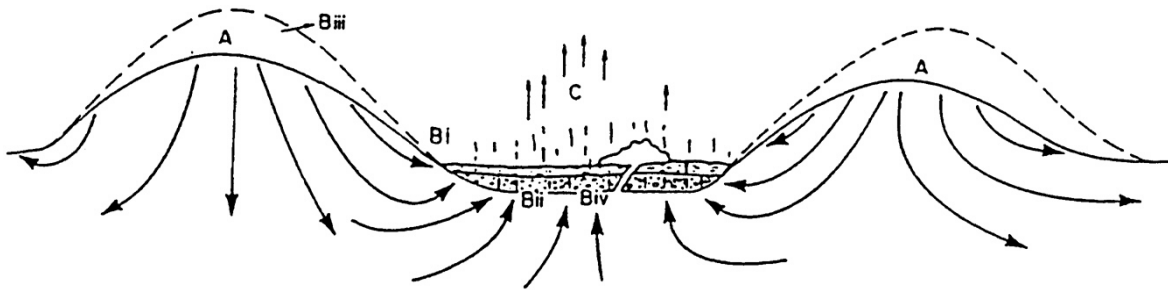


Figure. 3.2 Interpretation of the historic ground water flow system in the Basin of Mexico City. Infiltration of precipitation and snow melt in the surrounding mountains forms a deep water table (A) with downward gradients, some of which exits at shallow water tables (Bi) in the lower foothills or piedmont regions, and the majority flows under the valley floor and upward through the clays as diffuse discharge (Bii) and as thermal springs (Biv) through fractures in the deep aquifer. All discharge from the closed basin is by evapotranspiration [Durazo and Farvolden, 1989]

The geology of the south of Sierra Guadalupe is the best-investigated portion of the Basin of Mexico. This area, which contains Mexico City, is often referred to as the Valley of Mexico, because it is partially divided by several low mountains from the remainder of the basin. Likewise, the aquifer system in this region is often referred to as the Mexico City Aquifer. [NAS, 1995].

Superficial lacustrine clay deposits (i.e., the layer of clay at the former and existing lake bottoms) cover 23 percent of the lower elevations of the Basin of Mexico. The deposits are present in two formations divided by what are referred to as “hard layers” (Capa Duras) composed primarily of silt and sand. The Capa Duras occur between 10 and 40 meters deep and are only a few meters in thickness. The lacustrine clay layers, which reach to a depth of 100 meters, are considered to be an “aquitard,” because they are considerably less permeable than the Capa Duras or the underlying alluvial sediments. The Capa Duras produced the first artesian wells when ground water was exploited early in the 19th century. [NAS, 1995]

3.1.4 Hydrologic zones

Three major hydrologic zones are defined for the Basin of Mexico: the lacustrine zone described above, the piedmont or transition zone, and the mountain zone. The distribution of these zones can be inferred from the elevation map in Figure 3.3. The lacustrine zone corresponds to the lowest elevations. The piedmont region generally occurs between the historic lakebed and the steep mountains. Here, the lacustrine clays become interbedded with silts and sands, or, in the areas closer to the base of the mountains, the piedmont is composed largely of fractured basalt from volcanic flows. The basalt formation is highly permeable with good storage capacity, and is considered to be a component of the principal aquifer. [CNA, 2011]

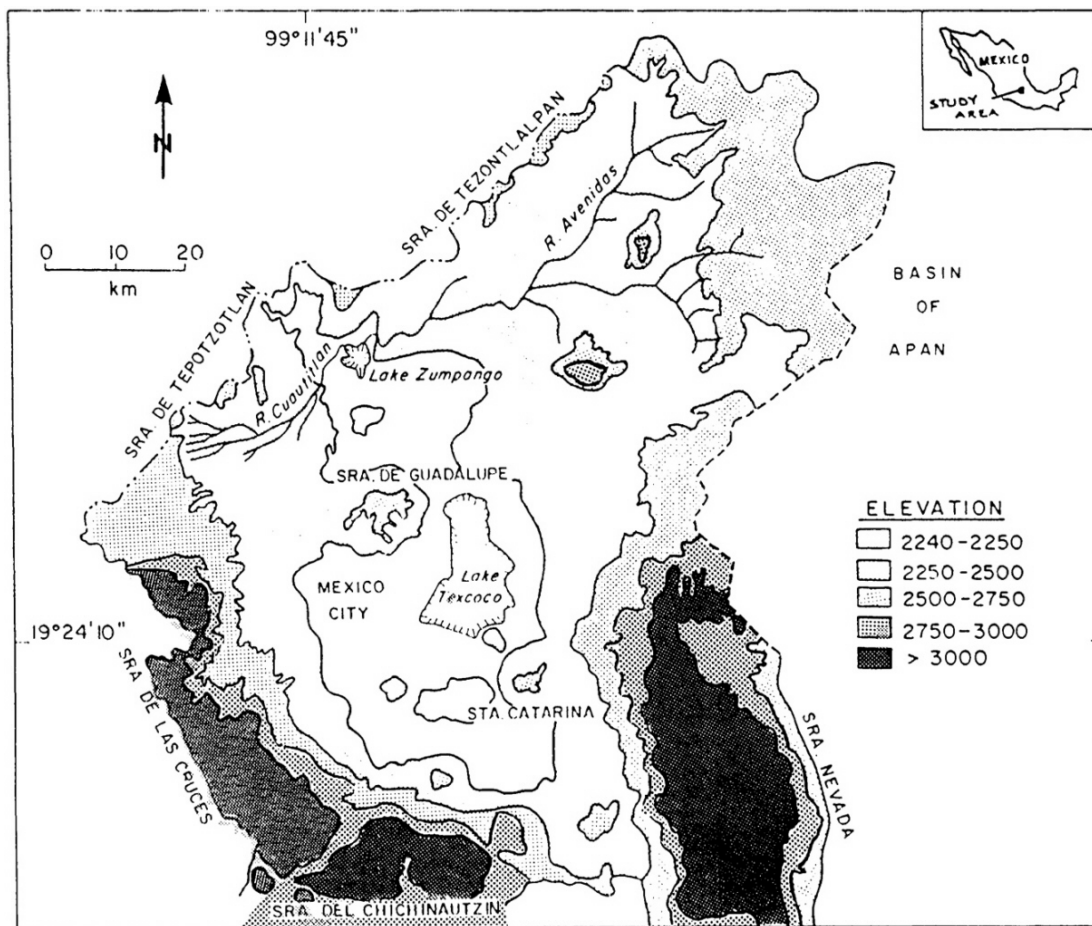


Figure 3.3 Hydrologic zones of the Basin of Mexico. The lacustrine zone occupies the lower elevations of the basin (clear). The piedmont region, or transition zone, occurs on the lower and upper slopes. The two highest elevation classes roughly correspond to the mountain zone. [NAS, 1995]

The piedmont (also known as the transition zone) is important for natural recharge of the aquifer. The mountains ringing the Basin of Mexico are volcanic in origin. The Sierra Nevada range is to the east and the Sierra de Las Cruces is to the West. The Sierra Chichinautzin to the south forms the most recent chain. Its eruption, approximately 600,000 years ago, blocked what was primarily a southerly drainage and effectively closed the basin. The Sierra Chichinautzin is the most natural important recharge zone for the Mexico City Aquifer due to the high permeability of its basalt rock. The large Xochimilco springs on the basin floor are a discharge point for the underground flow, and some of the most productive wells are located there. [NAS, 1995]

The Mexico City aquifer has two deeper permeable units: an intermediate and a deep aquifer. These are considered to be independent of the principal aquifer. The intermediate aquifer is composed of Miocene volcanic deposits (Units 9, 10, and 10a of Figure 3.4). The underlying Cretaceous limestone formation (Units 11a and 11b of Figure 3.4) may also be an aquifer. Where it is exposed outside the southern portion of the basin, it is currently exploited for ground water.

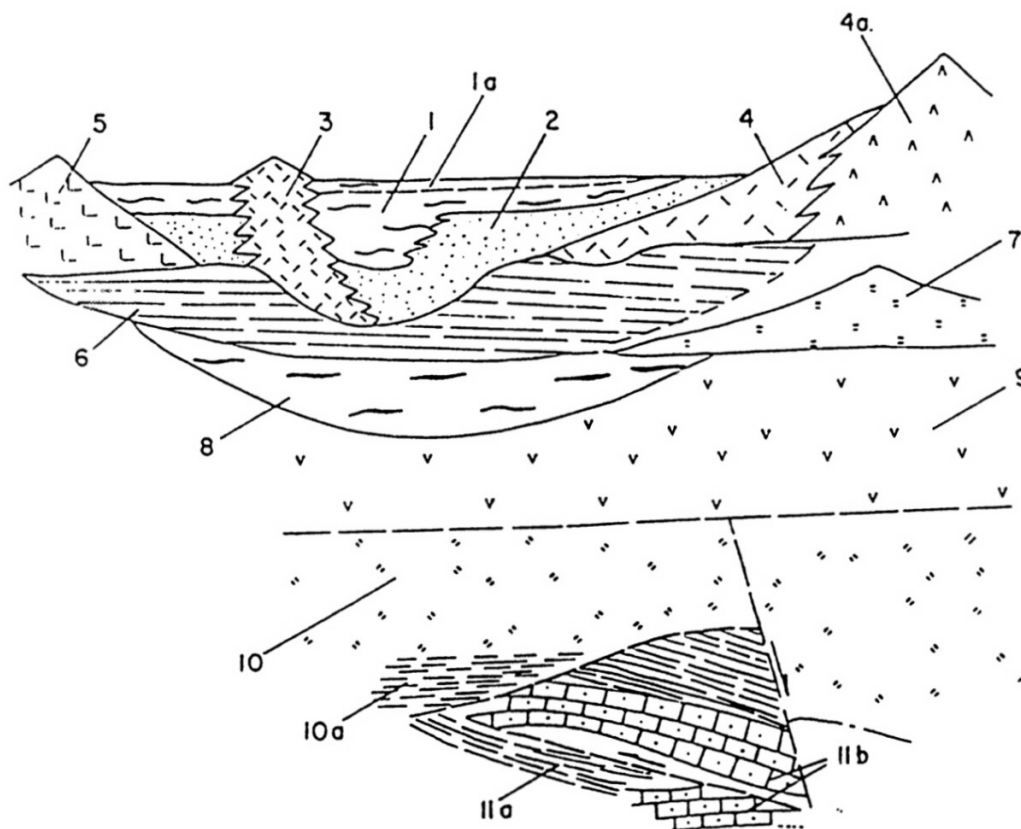


Figure 3.4 Mexico City aquifer. (1) The southern portion of the basin, exploited for ground waters as of 1995 (2) alluvial fill, (3) Pleistocene and more recent basalt including Sierra Chichinautzin, (4) Tarango formation, (4a) high mountain range, (5) volcanic hills and deposits, (6) stratified volcanic deposits, (7)

Pliocene mountain range, (8) Pliocene lower lacustrine deposits, (9) Miocene volcanic deposits, (10) and (10a) Oligocene volcanic deposits, (11a) and (11b) Cretaceous limestone platform. The upper portion of the main aquifer is composed of units (2), (3), and (4). The lower portion of the main aquifer is composed of unit (6). Units (9), (10), and (11) are considered lower aquifers distinct from the main aquifer in exploitation. [Mooser, 1990]

Historically, the principal aquifer and the shallow aquifer (or Capa Duras) were subject to artesian pressure so that all wells on the valley floor flowed at the surface without pumping. The natural hydraulic gradients caused water to move upward and through the overlying clay aquitards. In the 19th century, the proliferation of wells changed the natural hydrologic conditions. Now, the gradients and flow in the upper layers of the deposits are generally downward toward the heavily pumped zones. [NAS, 1995]

3.1.5 Water level declines in the aquifer and land subsidence.

In the 14th century, the Aztec city of Tenochtitlán made use of an elaborate system of aqueducts to carry spring water from higher elevations of the southern portion of the Basin down to the city situated on land reclaimed from the saline Lake Texcoco.

After defeating the Aztecs in 1520, the Spaniards rebuilt the aqueducts and continued to use spring water until the mid 1850s, when the discovery of potable ground water under artesian pressure motivated well drilling.

In the 20th century, increasing ground water extraction and artificial diversions to drain the valley resulted in the drying of many natural springs, shrinking of lakes, and a loss of pressure and subsequent consolidation of the lacustrine clay formation on which the city is built.

Consequent land subsidence has been a serious problem in the Mexico City Metropolitan area (MCMA) since the early 1900s. By 1953, it had been demonstrated that subsidence was linked to ground water extraction, and many wells inside the urban area were closed. [NAS, 1995]

The first signs of ground water level declines were the drying up of natural springs in the 1930s, coinciding with intensive exploitation of the main aquifer through deep wells (100–200 meter depths). In 1983, systematic monitoring of the water levels in the aquifer began. Since that time, the average annual declines in ground water levels range from 0.1 to 1.5 meters per year in the different zones of the city.

Water level measurements during the period from 1986 to 1992 show a net lowering of 6 to 10 meters in the heavily pumped zones of this region. [NAS,1995]

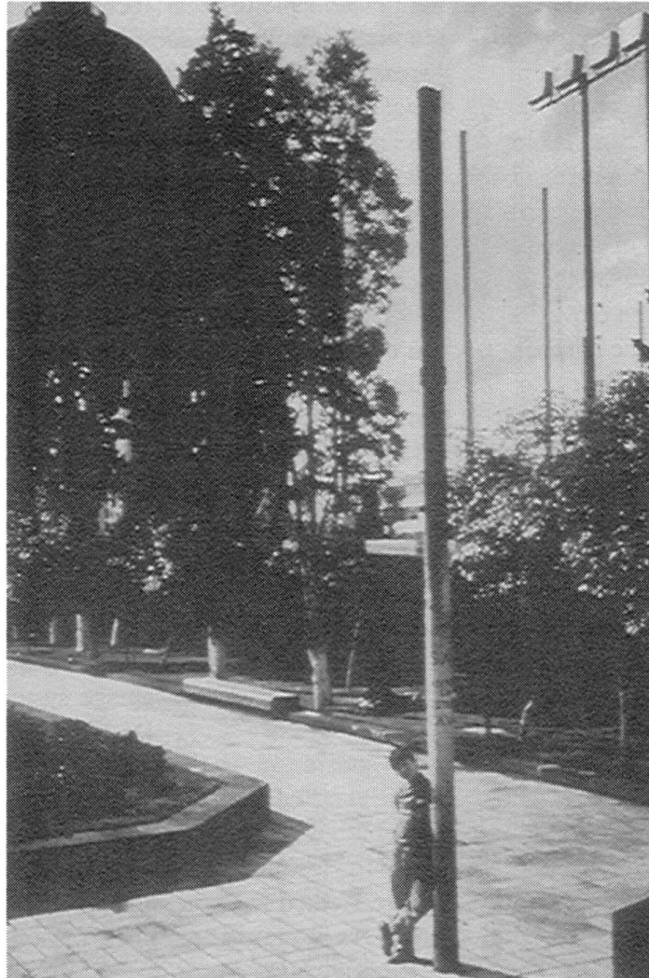


Figure 3.5 A well casing rising about 7 meters above the ground in a Mexico City neighborhood [Lesser-Illades et al. 1990].

When the shallow aquifer was pumped extensively in the mid to late 1800s, land subsidence was already in progress. By 1895, subsidence had reached an average of 5 centimeters per year. From 1948 to 1953, increased pumping rates, combined with deeper extraction wells, resulted in subsidence rates of up to 46 centimeters per year in some areas. [CNA, 2012]

According to the Mexico Valley Water Authority, the net subsidence over the last 100 years has lowered the central, urbanized area of the MCMA by an average of 7.5

meters. The result has been extensive damage to the city's infrastructure, including building foundations and the sewer system.

Figure 3.5 shows a well casing rising about 7 meters above the ground in a Mexico City neighborhood [Lesser-Illades et al. 1990].

One of the serious problems resulting from subsidence is the lowering of the elevation of Mexico City relative to Texcoco Lake, which is the natural low point of the basin. In 1900, the bottom of the lake was 3 meters lower than the median level of the city center. By 1974, the lake bottom was 2 meters higher than the city. These changes have aggravated the flooding problem and are reflected in the evolution of the complex drainage system to control flooding [CNA, 2012].

Moreover, in the early 1900s drainage of the city was conducted by gravity through the Grand Drainage Canal and out the Tequisquiac Tunnel at the north end of the valley. By 1950, the sinking of the city was such that dikes had to be built to confine the stormwater flow, and pumping was required to lift the drainage water under the city to the level of the drainage canal.

The relative rise of the lake level continued to threaten the city with flooding, and work on the deep drainage system and excavations to deepen Texcoco Lake had to be carried out.

Figure 3.6 shows progressive sinking of the city relative to the Grand Drainage Canal [NAS, 1995].

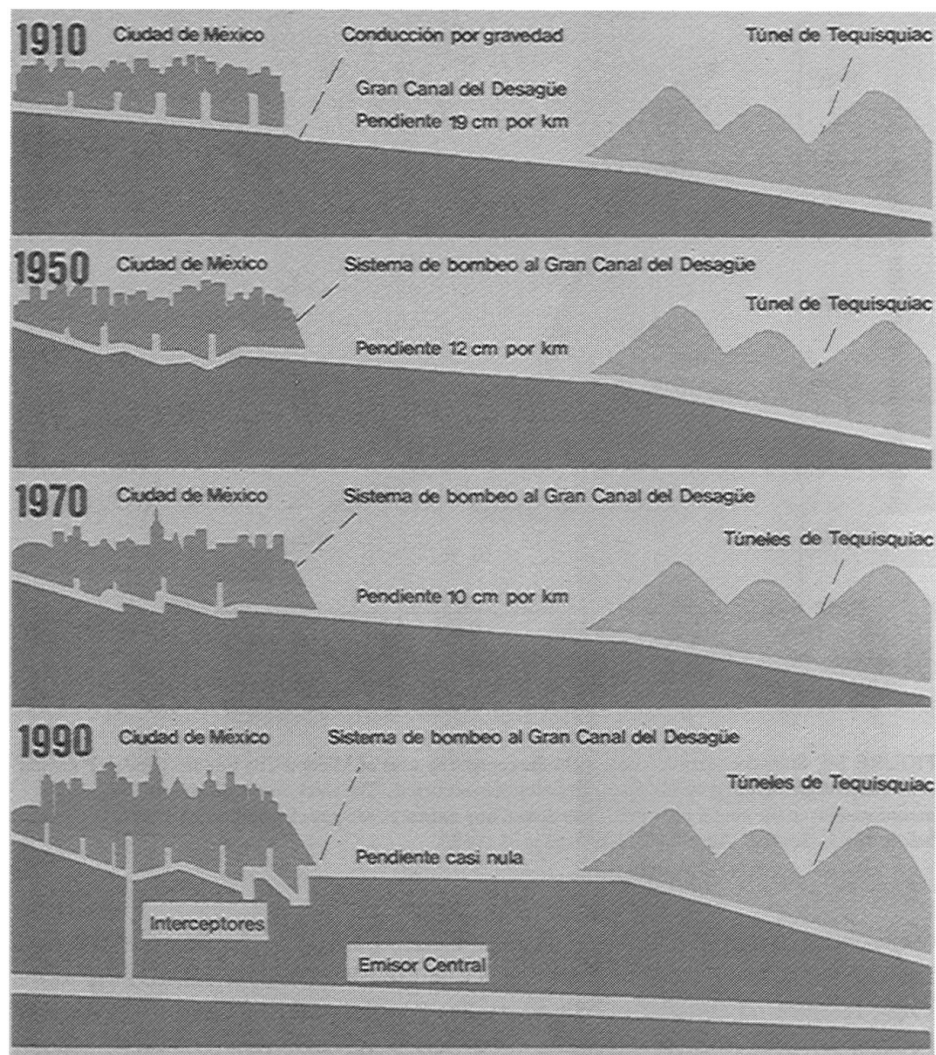


Figure 3.6 Progressive sinking of the city relative to the Grand Drainage Canal [NAS, 1995].

Furthermore, several lakes have formed in depressions created by lowered ground levels in the pumping area. As pumping continued, these lakes expanded. Figure 3.7 shows comparative subsidence in the city center area of Mexico City and the Chalco plain from about 1935 to the present. [Ortega et al. 1993]

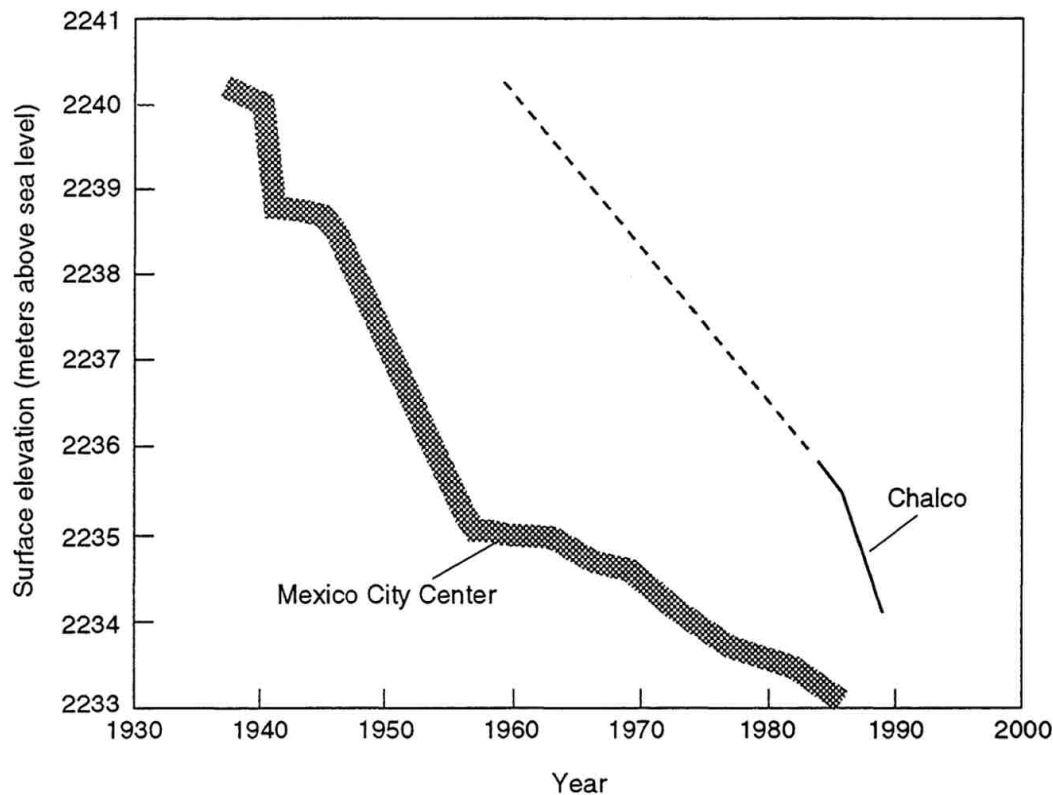


Figure 3.7 Comparative subsidence in the city center area of Mexico City and the Chalco plain from about 1935 to the present. [Ortega et al. 1993]

In 1925, Roberto Gayol did surveys that showed Mexico City was sinking, and stated that the cause was likely subsurface drainage related to the recently completed construction of the Grand Drainage Canal and the Tunnel of Tequisquiac. [NAS, 1995]. Furthermore, the relation between subsidence and exploitation of the aquifer was carefully examined since that time. Carrillo, (1948) was the first to develop a mathematical model linking subsidence to the hydrology, and in the following decades, modern ground water models were developed for the semiconfined, multiple aquifers in the southern portion of the Basin of Mexico City, and applied to the question of subsidence [Herrera and Figueroa, 1969; Herrera, 1970].

Moreover, in the 1990s, a network of 320 observation wells was created for determination of water level and flow direction. Every two years, since then, more than 1,400 surveys have been performed to gauge changes in subsidence.

Currently for the supply of water for Greater Mexico City, 470 million cubic meters from the Cutzamala System are received yearly, 151 million cubic meters from wells in the

Lerma River Basin and 85 million cubic meters of dams that collect water from rivers and springs within the valley. In addition, 1.876 million cubic meters per year are extracted from the aquifer; and these accounts for a total of 2.583 million cubic meters annually. [CNA, 2012]

The rapid and uncontrolled growth of the urban area and the overexploitation of aquifers cause a serious water imbalance, as currently more than twice of the recharge rate is extracted from the aquifers. The origin of subsidence, according to Dr. Nabor Carrillo is the pressure loss in the confined aquifer, caused by pumping which produces a compression process. Figure 3.8 shows another example of a water pump casing that is elevated above ground level due to subsidence.



Figure 3.8 Water pump showing the soil subsidence. [Luege, 2012]

Since 1891, there are references of sinking in various areas of the City, with an accelerating process in recent decades, reaching alarming proportions in the Valle de Chalco and Ciudad Nezahualcoyotl, and delegations Venustiano Carranza, Iztacalco, Xochimilco, and Gustavo A. Madero; areas of the City which present frequent flooding [CNA, 2012]. In addition, the drainage works built for waste water and rain water during

the decades have been exceeded by the demand and in cases have reduced their capacity due to the sinking which reduces the slope of the drainage [Luege, 2012].

	1975	2007	2010
	Capacity [m ³ /s]		
Grand Drainage canal	80	15	45
East drainage	30	30	30
Central drainage	170	120	120
Total	280	165	195
Million inhabitants	10	19	20

Table 3.1 Drainage networks in the Valley of Mexico are insufficient. [Luege, 2012]

The capacity of the drainage system of the metropolitan area is insufficient and is an obstacle for the sustainability of the region. This confirmed by comparing the capacity it had in 1975 (280 m³/s) to 2010 (195 m³/s). This decrease is attributed to the collapse of more than four meters on average suffered Mexico City during the period 1975 to 2007 (see Table 3.1). In addition, the occurrence of storms and heavy rainfall of unprecedented magnitude in the Valley of Mexico increase the risk of severe flooding. It should be noted that the Central Drain, built to carry rainwater in storm peaks, operated for over 15 years beyond its design capacity and is used continuously without maintenance (see figure 3.9). In addition, this drain conducts wastewater, disrupting its original design of rainwater conduction, which also causes accelerated wear [Luege, 2012].



Figure 3.9 Internal deterioration of the Central Drain. [Luege, 2012]

3.1.6 Water sustainability in the Mexico City catchment.

With the premise that water is a matter of national security, the government of Mexico presented in November 2007 the Water Sustainability Program of the Basin of Mexico, which aim is to to recover the water balance in the region and contribute to the viability of the metropolitan area in the medium and long term. The objectives of the program are:

- Recover water bodies and surface wastewater channels in urban areas.
- Reverse the overexploitation of aquifers from wells by industry or agriculture as well as by incorporating new sources of drinking water.
- Expand the capacity of the drainage system (sewage and rainwater) Metropolitan Area.
- Treat 100% of wastewater in the Valley of Mexico.
- Reduce leakage in the distribution system of drinking water in the metropolitan area.
- Implement the comprehensive management of the basin.
- Protect and increase the extent of forested areas of the Valley of Mexico to promote the presence of rain and allow natural recharge.

The reduction of leakage in the hydraulic network is considered essential for achieving the hydrological balance in the region. To help solve the current problem, the federal government has invested in several emergency constructions such as the four pumping stations to increase the flow in the Grand Channel and the West Drain to an additional 30 m³/s. This partial recovery of the carrying capacity of the Grand Channel Drainage allowed for the inspection of the Drain and to make urgent repairs necessary. [CNA, 2012]

Furthermore, in August of 2008 the construction of the East Drain started. According to Luege (2012), this tunnel will thoroughly solve the problem of the drainage system as it will provide an alternative to the Central Drain, and is expected to reduce the risk of flooding in the city and its suburbs considerably. Moreover, during the rainy season, it will run simultaneously with the current drainage. (Figure 3.10)

This tunnel, with a capacity of 150 m³/s will avoid the risk of flooding in the city and its suburbs, protecting their inhabitants. The tunnel construction is delayed and authorities estimate it will be finished in 2018.



Figure 3.10. East Drain. View of the final lining work with slipform. [Luege, 2012]

The Eastern Drain not only will double the drainage capacity of the Basin of Mexico, but it will also conduct the wastewater to the new treatment plant built in Atotonilco de Tula, Hidalgo, with a nominal capacity to treat 23 m³/s of wastewater. (Figure 3.11)

Scheduled to be completed in late 2017, this treatment plant will provide pathogen free water to irrigate 80,000 hectares for agriculture, and will clean up to 60 % of the wastewater generated in the Valley of Mexico, where currently only 11 % is treated.



Figure 3.11 Construction of the wastewater treatment plant in Atotonilco. [Luege, 2012]

In addition, this plant will substantially improve the health conditions of the inhabitants of the region for whom the incidence of various waterborne diseases will be reduced, and the farmers will have the option to develop more profitable crops. Furthermore, the Atotonilco plant does not generate pollution with methane, which is a greenhouse gas, as the methane will be exploited to produce up to 70 percent of the electricity required by the plant. [Luege, 2012]

As mentioned above, the rapid population growth in Mexico City has increased the need for water supply and resulted in more groundwater extraction. The water has been pumped from below the city, which has actually caused the city to sink. In the last 100 years, parts of Mexico City have sunk as much as forty-two feet. [Luege, 2012]

Therefore, the East wastewater tunnel is planned to work together with the Atotonilco water treatment plant which will reduce the need of extraction of deep water in the Mexico City Valley.

Chapter 4. HYDRO-METEOROLOGICAL DATA IN MEXICO.

Summary.

To set a design flow without having a hydrometric station, the method used commonly is to obtain rainfall data in and around the basin that feeds the river of interest. There are different levels of detail of rainfall studies that can be performed, depending on the information. The conversion of rainfall in the catchment to runoff that reaches the river is done through so-called rainfall-runoff models. This chapter presents an outline of the hydro-meteorological data available in Mexico.

4.1. Meteorological data.

In the most typical conditions rainfall data available have the following characteristics:

- Temporal resolution of one day,
- A density of precipitation stations not less than one station every 400 km².
- The period of time covered by each station will be different. For example, records from 1939-1988 in one station and 1959 to 2005 for another station. The intervals common to all stations will generally be much shorter than the typical interval for each station individually.
- Each rainfall record will have a certain fraction of voids or days with missing data. The days without data generally will not match from one station to another. Once the basin of interest is defined, station locations within or in the vicinity thereof are identified. Here it is necessary to emphasize that the important thing is to have the exact geographical distribution of rainfall within the basin. [CNA, 2012]

Once the rainfall records of each of the stations are obtained, it is necessary to select the cases of significant rain that could end up providing the highest discharges to the channels or streams of interest for each year. [Aparicio, 2001]

4.1.1 Methods to obtain the rainfall distribution.

Depending on the rainfall-runoff model to be used, what is sought is an average rainfall for the entire basin in the day under study (for lumped parameter models) or a distribution of the rain that day inside the basin (for models of distributed parameter). The latter are physically superior to the first but, even today, the former are much more common. [CNA, 2012]

Traditionally several options to calculate the average values within the basin are considered:

- The arithmetic average
- Average for Thiessen polygons
- Inverse Distance Weighting (IDW),
- Spline,
- Ordinary Kriging (OK),
- Geographically weighted regression (GWR)

The arithmetic average has no physical basis and should be avoided in all applications except when rough estimates are done in the field, and it makes sense only when the stations are equidistant.

The method of Thiessen polygons has a very intuitive physical basis and is relatively easy to manually apply. Its main disadvantage is that a different set of Thiessen polygons must be developed for each distinct combination of measuring stations. [CNA, 2011]

The IDW was developed by the U.S National Weather Service in 1972, that interpolation method determines cell values by using a weight average of sample points in the neighborhood [Goovaerts, 2000].

With the IDW method, the accuracy of interpolated values will decrease if the neighboring points are unevenly distributed. There are many different forms of IDW interpolation, but the simplest form is proposed by Shepard (1968).

The Spline method is an interpolation method that estimates values using a mathematical function that minimize overall surface curvature, resulting in a smooth surface that passes exactly through the input points [Tao, 2009].

The Kriging method consists of a family of least-square linear regression algorithms used to estimate random fields from which observed data are considered to be drawn as a sampling of a field realization. [Goovaerts, 1997, 1998; Tobin et al., 2011]

The weights of Kriging are based not only on the distance between the measured points and the prediction location but also on the overall spatial arrangement of the measured points.

The geographically weighted regression, is a method developed to interpolate spatially the rainfall. [Brunsdon et al., 1998] It is a local spatial statistical method used to examine and determine the spatial non stationary, when the relationships among variables vary from location to location [Fotheringham et al., 2003]

4.1.2 Analysis of rainfall.

The precipitation occurs as rain, snow, hail, among others; and in Mexico often the most important is the first one, although there are some areas in parts of the North where melting snow can cause major avenues.

In the hydrologic analyzes the basic characteristics of precipitation are:

- Height of precipitation: The amount of water that precipitates during a storm in a given time; its units are usually expressed in mm. It is also known as rain sheet.
- Precipitation intensity: It is the amount of water that falls in a certain time, expressed in mm / h.
- Duration: It is the time interval in which the precipitation occurs, expressed in hours.

For representative precipitation over a basin, first an analysis of the data recorded in each of the stations in the basin is required. The precipitation characteristics are different in each basin. Hence precipitation data recorded in different areas only provide an adequate approximation of precipitation in the immediate region where the measurement was performed. [CNA, 2012].

According to Chow (1964) a small basin is one that is sensitive to high rainfall intensity and short duration, i.e. prevailing physiographic basin characteristics on the streams. Chow set as the limit for considering a small basin one that is less than 25 km².

For practical purposes it is proposed to use the basin size classification shown in Table 4.1.

Basin size (km ²)	Classification
<25	Very small
25-250	Small
250-500	Intermediate-Small
500-2500	Intermediate-Large
2500-5000	Large
>5000	Very large

Table 4.1 Basin classifications by size. [Chow, 1964]

In Mexico, a conventional weather station is a small outdoor installation about 3 x 4 meters within a lattice of approximately 1.20 m in height. [CNA, 2012]

Typically it has the following instruments:

- A gauge that captures rainwater in a cone of standardized dimensions and placed in a cylinder with cross-sectional area to make readings
- Two mercury thermometers that measure the ambient temperature and record the maximum and minimum ends of the column. These are sheltered in a small wooden house, allowing free passage of air therethrough, but preventing the solar radiation to fall directly onto them,
- An evaporimeter where the evaporation film is measured daily with a vernier screw mechanism.
- A small mast with a weather vane and a plaque that allow to qualitatively assess the speed and wind direction.

Every morning, usually at 8:00 AM, an operator manually measures the levels of precipitation and evaporation of the last 24 hours, instant room temperature and the maximum and minimum temperatures reached in the last 24 hour. Also notes whether in the last 24 there was fog, thunderstorms or hail. He also notes the perception of the sky as clear, partly cloudy or cloudy. [CNA, 2011]

About the wind, at 8:00 AM it is often totally calm and this is not a variable that is recorded in the national climatological data base (BDCN).

The operator makes records of the measurements and observations in a notebook, then withdraws and empties the gauge, restores the level of water in the evaporation pan (if necessary) and returns maximum and minimum markers of the standard thermometer to their starting positions.

Moreover, approximately 5,000 weather stations have operated over time in Mexico, and the maximum numbers of stations that have been operating simultaneously were 4,300. Today there are around 3,300. Measurements of these weather stations represent the backbone of the network of atmospheric measurements of the country [CNA, 2012]. Nominally, once each month, staff of the CNA collects data and sends them to state or regional offices.

A subset of these stations have access to phone (formerly radio and even before a telegraph) so to transmit their data immediately after making measurements at sites of concentration giving access to the CNA, in what might be called "real time" for a network of this type. The subset of near real time is about 900 stations. It is this subset from which daily precipitation maps are obtained. [CNA, 2011]

4.1.3 The Climatological Data Base of Mexico (BDCN)

The BDCN is the dataset of weather stations that have so far been digitized. It is internally organized into records that group a month of measurements of a single variable in a single season. Thus, all measurements of a station during the 31 days of May 1999 make a record. This may facilitate the interpretation of the total volume of data available, as this is reported usually using the "records" as units. [CNA, 2011]

Each season has different operating ranges, typically identified with a start date of operation and an end date of operation, but can also have several segments. For example, a station may have operated February 1948 to September 1986 and again from July 1990 to November 2008. The fact that a specific day, such as June 25th of 1957, is in the interior of these intervals does not guarantee that measurement for that day exists, during that season of the variable of interest. This is because even within these intervals there is a certain nominal porosity, (i.e. missing values that are marked with a conventional flag). [Luege, 2012]

Thus, to characterize the true availability of data, it is done through the start and end dates of operation and the percentage of the nominal data in that range available. In the previous example:

Chapter 4 – Hydro-Meteorological Data In Mexico

- February 1948 to September 1986 92%
- July 1990 to November 2008 84%

Furthermore, complete uniformity in all variables for the same station on the same date cannot be expected. Some of them may contain the banner of "lack of information" and the other may exist.

It is important to differentiate between the number of stations operating in a certain historical period and the number of available stations at that time. Moreover, there is always the possibility that some operating station at one time have lost their original records. [CNA, 2012]

Several interesting features are observed:

- In 1902-1909 the number of stations operating grew modestly. The Mexican Revolution of 1910-1920 reversed this trend.
- In 1921-1983 the number of operating stations grew, with some fluctuations but with a clear upward trend.
- From 1984-1993 there was a significant decrease until 2007 and then it stabilized.
- In early 1990 an intensive effort to capture data from 1961 to 1990 was performed. Indeed for more than 10 years after that captures the increase in digital data availability between 1961 and 1990 was obvious. But a capturing effort has been made from about 2002 to currently. Today we have a relatively high availability of digital data not lower than 85% at any time. [CNA, 2011]

It should be noted that the technology used in traditional weather stations in Mexico is very old. Without equivocation it can be assured that equivalent instruments existed since 1850 (although at higher prices than current). Moreover, it is difficult to finely manage a system that has 3,300 workers distributed throughout Mexico that are not supervised more than occasionally by formal employees of the operating institutions. Under these conditions the control and quality assurance are very difficult tasks to perform [CNA, 2012]. On the other hand, strong asymmetries are generated in the investments made.

On one hand the cost of travel for data collection is very high when compared with the amount of data collected at each site. On the other hand, despite more is spent to obtain and collect measurements than in digitizing the data, the fact is that the first is done but the second tends not to be done (at least timely). That is, money is spent in collecting but the extra pennies are not spent to make the data actually available. [CNA, 2012]

Some of these problems can be solved with automatic measuring equipment, but at relatively high costs. In recent years, new technologies have cheapened the price of an Automatic Weather Station (AWS) and this solution begins to be feasible, although, so far there have only been operational test programs of this type of equipment. Like many other technological changes, it is necessary to overcome the existing inertia. [Luege, 2012]

However, it is foreseeable that in the relatively near future, the system could have at least hourly measurements that define the climatology of the diurnal cycle, the data are digital of origin and these do not depend on the handling of one of the 3,300 different operators.

CNA (2011) stated that never such an important system for Mexico has received so little support to operate, ideally in perfect conditions (exact, accurate, timely, available to all, with density related to the phenomena that seeks to define, with appropriate technology, etc.). Still, the wealth within the database is outstanding and, paradoxically, even today underutilized.

4.2 Physiographic and hydrological data

Physiographic data are the area, terrain and vegetation cover in the basin, slope and length of the main channel, topography and geology of the area, among others. In Springall (1970) a description of physiographic features and how to calculate them can be consulted.

A difficulty that arises in the hydrological design is to have information of rain, runoff, evaporation, temperature, etc. In Mexico these can be obtained in existing hydrological bulletins published by the CNA, through CDs, by the Federal Electricity Commission (CFE), the National Weather Service (NWS) and in the International Commission Boundary and Water Commission (IBWC). [CNA, 2011].

Following, a description of the database for surface water data of Mexico (BANDAS), which was used in the present study, will be given.

This database of surface waters includes: flows in rivers, sediment transport in rivers, the free surface levels in rivers and storage in dams. The available data are daily, monthly averages and annual averages. These data come broadly from the hydrometric network of the National Water Commission (CNA), which operates through its Basin Organizations and Local Offices coordinated by the Management of Surface Water and River Engineering and it served to carry out the deterministic hydrological model of Mexico City catchment.

Chapter 4 – Hydro-Meteorological Data In Mexico

The catalog of hydrometric stations has listed 2,175 different locations on the national territory, while the catalog of dams list 168. The numbers of years of registration and the specific ranges for them are different in each station. Figure 4.1 and figure 4.2 show two different stations in the states of Hidalgo and Puebla.



Figure 4.1 Hydrometric station in the state of Hidalgo. [CNA, 2011]



Figure 4.2 Hydrometric station in the state of Puebla. [CNA, 2011]

PRS is a product generated by the Mexican Institute of Water Technology (IMTA) under contract by the National Water Commission.

PRS can be distributed freely to the interested population in a set of 10 CDs, corresponding to the hydrometric stations in riverbeds and on the operation of dams. [CNA, 2011].

Furthermore, in the SIAS application of Mexico (SIAS is an acronym for Information System of Surface Water), in which the measured raw data are captured in hydrometric stations such as: reading scales, summaries and sediment gauging and hydrometric processes. Mathematical calculation is performed where products are: average daily discharge, instant discharges, monthly and annual data and charts, the relevant flows, rating curves, hydrographs, etc, and the weather information (rainfall and evaporation) is captured.

It is important to note that hydrometric data in Mexico City is not available for several years since records began, and this leads to difficulties when validating and calibrating the results of hydrological models. [CNA, 2011]

Chapter 5. THE MODELING APPROACH: STRATEGY, DATA AND APPLICATION

Summary.

Mexico City is facing problems of flooding in some areas at certain times of the year, causing important losses and damages on properties and residents including some casualties. Therefore, it is important to carry out a flood risk assessment in the catchment of Mexico City and estimate damages of probable flood events. However, limited data of observed discharges and water depths in the main rivers of the city are available, and this represents an obstacle for the understanding of flooding in Mexico City. The premise of this study is that with the limited data and resources available, the catchment can be represented to an acceptable degree by the construction of a deterministic hydrological model of the Mexico City basin. The objective of the developed tool is to provide an efficient support to management of the flood processes by predicting the behavior of the catchment for different rainfall events and flood scenarios. The capability of a model based on MIKE SHE modeling system for the Mexico City catchment was evaluated by comparing the observed data and the simulation results during a year after a careful development based on the most important parameters for characterizing the processes. Significant and operational results (>0.7 for Nash Sutcliffe coefficient) have been obtained on one of the major sub-catchments of the Mexico basin. These results demonstrate the interest to implement a deterministic hydrological model for assessing flood risks in a dense urban environment where data availability is limited. Furthermore, the resulting discharges from the hydrological model in MIKE SHE in rivers were used to carry out a flood hazard assessment. The discharges in 7 rivers and the water level downstream were input in MIKE 21 as boundaries for the model. Moreover, these results were used in the MIKE 21 model for assessing the extent of the areas of flood risk and the flood depth in Mexico City. In addition, a grid size sensitivity analysis was carried out for the topography used in MIKE 21. Grid sizes of 50 m, 30 m and 20 m were used in a MIKE 21 model to create flood maps and analyze the differences in flood extent and depth.

5.1 Deterministic hydrological model of Mexico City.

5.1.1 Methodology

For the Mexico City Valley, and based on the selection criteria for modeling methods in section 1.6, the suggested methodology for this study is based on the implementation of a hydrological model using the MIKE SHE and MIKE 11 modeling system. In addition, discharge and water level data in the Mexico City catchment, are available for only a limited number of years, and daily precipitation data is also available for a few years in Mexico City; some of which coincide with the discharge data available. Therefore, the precipitation and the DEM data were used to build a hydrological model and simulate discharges in rivers using MIKE 11 and MIKE SHE. This software, however, has the capability to include more components in the model and increase its complexity regarding land use, soil types, unsaturated and saturated zones, groundwater and several other parameters due to its modular set up, in which the different components can be activated or de-activated for each new simulation. In addition, thanks to the Polytech Nice- Sophia, this software was available for unreserved use during this research, as opposed to other softwares, which were also considered.

The analysis will evaluate the discharges in several rivers of the City and compare the estimated values with gauged data to see whether the model can represent the full hydrological process with sufficient accuracy for the operational management of the catchment.

Figure 5.1 outlines the methodology followed for the hydrological model of Mexico City and the flood modeling for risk assessment.

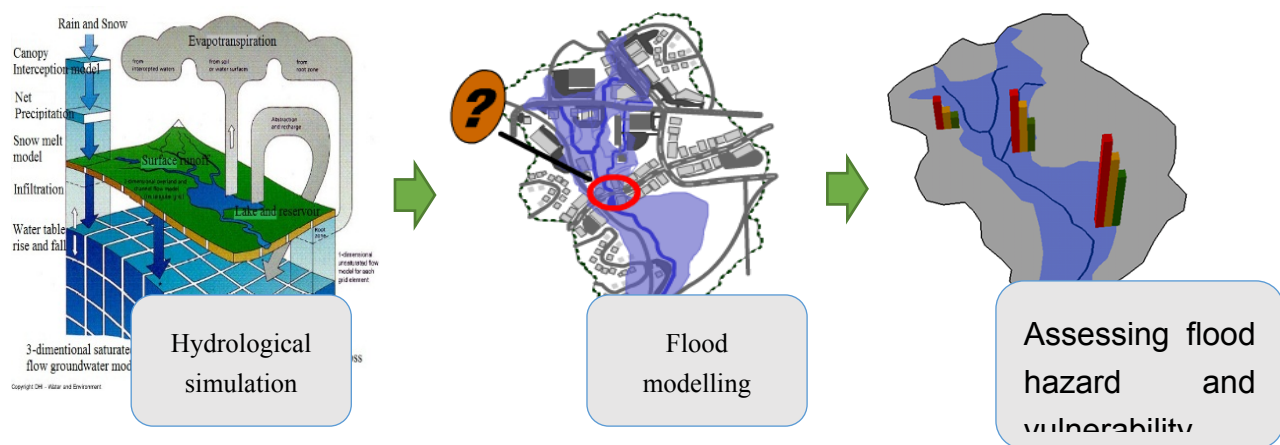


Figure 5.1. Methodology for estimating the flood hazard in Mexico City.

MIKE SHE allows the simulation of all the processes in the land phase of the hydrologic cycle. That is, all of the process involving water movement after the precipitation leaves the sky. Precipitation falls as rain or snow depending on air temperature - snow accumulates until the temperature increases to the melting point, whereas rain immediately enters the dynamic hydrologic cycle. Initially, rainfall is either intercepted by leaves (canopy storage) or falls through to the ground surface. Once at the ground surface, the water can now either evaporates, infiltrate or runoff as overland flow. If it evaporates, the water leaves the system. However, if it infiltrates then it will enter the unsaturated zone, where it will be either extracted by the plant roots and transpired, added to the unsaturated storage, or flow downwards to the water table. If the upper layer of the unsaturated zone is saturated, then additional water cannot infiltrate and overland flow will be formed.

This overland flow will follow the topography downhill until it reaches an area where it can infiltrate or until it reaches a stream where it will join the other surface water. Groundwater will also add to the base flow in the streams, or the flow in the stream can infiltrate back into the groundwater. [DHI, 2012]

Overland flow is required when MIKE 11 is coupled with MIKE SHE, as the overland flow module provides lateral runoff to the rivers. The overland flow can be calculated using either a semi-distributed method or a finite difference method. The finite difference method should be used when the interest is in calculating detailed overland flow, while the semi-distributed, simplified method should be used for regional applications, where detailed overland flow is not required. [DHI, 2012]

Moreover, when the rainfall rate exceeds the infiltration capacity of the soil, water is ponded on the ground surface. This water is available as surface runoff, to be routed downhill towards the river system. The topography and flow resistance, as well as the losses due to evaporation and infiltration along the flow path determine the exact route and quantity. The water flow; on the ground surface, is calculated by MIKE SHE's Overland Flow Module using the diffusive wave approximation of the Saint Venant equations [DHI, 2012]

As the dynamic solution of the two-dimensional St. Venant equations is numerically challenging, the complexity of the problem is reduced by eliminating some terms of the momentum equation, therefore ignoring momentum losses due to local and convective acceleration and lateral inflows perpendicular to the flow direction. This is known as the diffusive wave approximation, which is implemented in MIKE SHE [DHI, 2012]. The simplified form of the Saint Venant equations is:

$$S_{fx} = \frac{\delta}{\delta x} (z_g + h) = -\frac{\delta z}{\delta x} \text{ (Eq. 9)}$$

$$S_{fy} = \frac{\delta}{\delta y} (z_g + h) = -\frac{\delta z}{\delta y} \text{ (Eq. 10)}$$

where S_f is the friction slopes in the x- and y-directions, the ground surface level is $Z_g(x, y)$, and the flow depth is $h(x, y)$.

Use of the diffusive wave approximation allows the depth of flow to vary significantly between neighbouring cells and backwater conditions to be simulated. However, as with any numerical solution of non-linear differential equations numerical problems can occur when the slope of the water surface profile is very shallow and the velocities are very low. [DHI, 2012]

In this work, data inputs were first collected and processed according to the format of the software MIKE SHE coupled with MIKE 11. These inputs include: DEM, rainfall, river geometry, land use map, soil map, boundary conditions of discharge and other parameters. The model was set up using the input data along with the methods for the physical processes. In terms of processes, while the overland flow used the method of finite difference, the river flow employed the wave approximation of high order fully dynamic, which is used for relatively steep rivers without backwater effects. There are four possible flow descriptions available in MIKE 11. The flow descriptions can be selected globally for the system and/or locally for individual branches. Locally specified flow descriptions must be specified for the whole branch. In general it is recommended to use the ‘fully dynamic’ or the ‘high order fully dynamic’ flow descriptions. Only in cases where it can be clearly shown that the ‘diffusive wave’ or the ‘kinematic wave’ are adequate should they be used.

The latter two flow descriptions are simplifications of the full dynamic equations. These are provided to improve the computational efficiency of models in specific circumstances. [DHI, 2009] The hydrodynamic module of MIKE 11 provides fully dynamic solution to the complete nonlinear 1-D Saint Venant equation:

$$\frac{\delta u}{\delta t} + u \frac{\delta u}{\delta x} + g \frac{\delta h}{\delta x} + g(S - S_f) = 0 \text{ (Eq. 11)}$$

The coupling between MIKE 11 and MIKE SHE is made via river links, which are located on the edges separating adjacent grid cells. Because the water exchange occurs along the

edges of the grid, it is noticed that the more highly resolved the grid, the more accurate the representation of the river network will be. Locations of MIKE SHE river links are determined automatically with reference to the co-ordinates of the MIKE 11 river points that define the branches of the hydraulic model. During a simulation, water levels within the coupled reaches are transferred from MIKE 11 H-points (points along the river model for which water levels are calculated); in turn MIKE SHE calculates the squares and the river-aquifer exchange. These terms are fed back to the corresponding MIKE 11 H-points as lateral inflows or outflows for the next computational time step. (Figure 5.2)

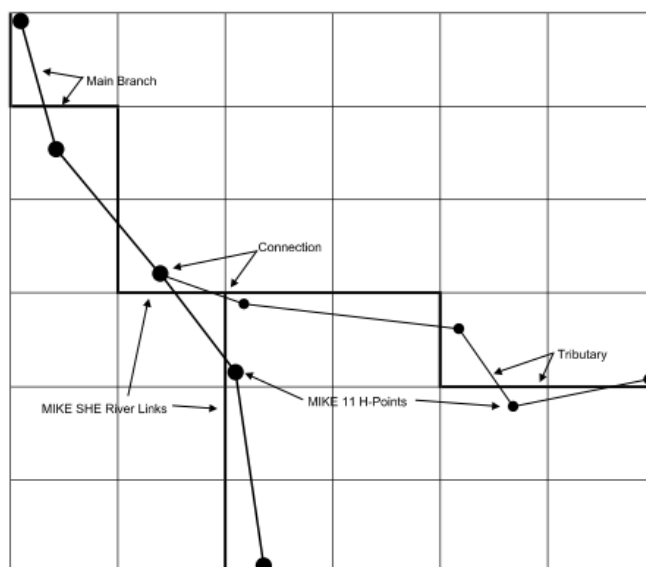


Figure 5.2 MIKE 11 Branches and H_points in a MIKE SHE Grid with River Links [DHI, 2012]

In MIKESHE 2012 modelling system, the exchange of water between MIKE 11 and MIKE SHE is calculated based on the river-link cross-section whose shape is triangular interpolated from the two nearest MIKE 11 cross-sections. The top width is equal to the distance between the cross-section's left and right bank markers. The elevation of the bottom of the triangle equals the lowest depth of the MIKE 11 cross-section (the elevation of Marker 2 in the cross-section). The left and right bank elevations in MIKE 11 (cross-section markers 1 and 3 in MIKE 11) are used to define the left and right bank elevations of the river link. (Figure 5.3)

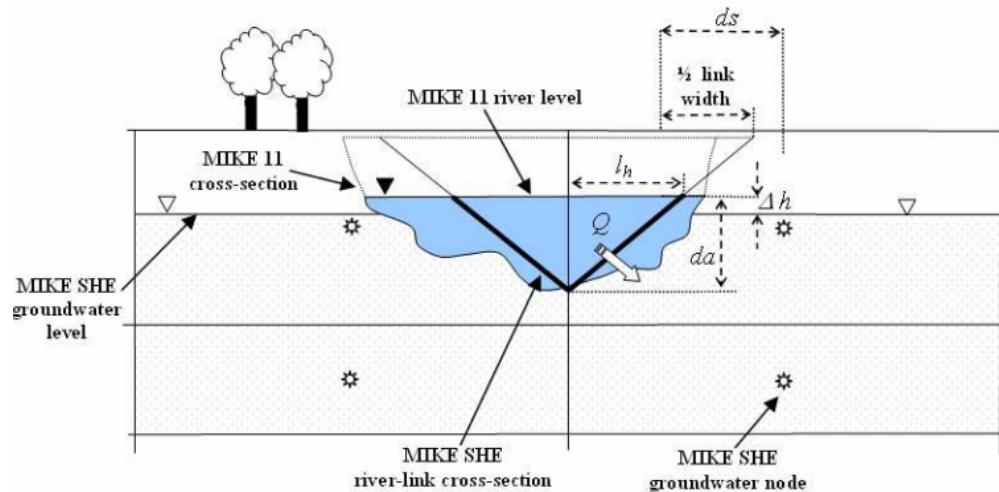


Figure 5.3 A typical simplified MIKE SHE river link cross section compared with the equivalent MIKE11 cross section (DHI 2012)

Regarding flow in the unsaturated zone, there are three options in MIKE SHE for calculating vertical flow:

- The full Richards equation, which requires a tabular or functional relationship for both the moisture-retention curve and the effective conductivity,
- A simplified gravity flow procedure, which assumes a uniform vertical gradient and ignores capillary forces, and
- A simple two-layer water balance method for shallow water tables.

In this study, the two-layer method was used, as no data on the water table characteristics of Mexico City are available.

For the Mexico City basin, the model is based on the most relevant variables, which may produce results with a reasonable accuracy. In order to define the most efficient approach, three scenarios were considered with different levels of complexity:

a. A hydrological model for the Mexico City catchment has been developed, the following components included:

- a Digital Elevation Model (DEM) with a resolution of 5 meters and an area of 2800 Km², provided by the Institute of Statistics and Geography of Mexico (INEGI);
- the daily rainfall values from the measuring stations available and for the duration of the simulation period;
- and a river network composed with cross sections extracted from the DEM.

b. A second model for the Hondo river sub-catchment in Mexico City with all of the above components and additionally, a distribution of roughness values used for runoff according to land use.

c. Finally, a third model for the Hondo river sub-catchment including all of the components of model 2, plus the unsaturated zone component.

The accuracy of the three models when representing the hydrological processes is assessed by quantification and evaluation of the root mean squared error RMSE and of the Nash Sutcliffe coefficient E, presented in equations (12) and (13) respectively:

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (X_{obs,i} - X_{model,i})^2}{n}} \quad [12]; \quad E = 1 - \frac{\sum_{i=1}^n (X_{obs,i} - X_{model,i})^2}{\sum_{i=1}^n (X_{obs,i} - \bar{X}_{obs})^2} \quad [13]$$

where X_{obs} is observed values and X_{model} is modeled values at time/place i .

Nash-Sutcliffe efficiencies can range from $-\infty$ to 1. An efficiency of 1 ($E = 1$) corresponds to a perfect match of modeled discharge to the observed data. An efficiency of 0 ($E = 0$) indicates the model predictions are as accurate as the mean of the observed data, whereas an efficiency of less than zero ($E < 0$) occurs when the observed mean is a better predictor than the model. The closer the model efficiency is to 1, the more accurate the model will be. In addition the lower the RMSE will be, and the better the model simulation performance.

Furthermore, a study by Bathurst et al. (2004) revealed model evaluation criteria for multi-site validation. These authors stated that spatially distributed models couldn't be considered fully validated unless they are able to reproduce internal as well as external responses. Moreover, the evaluation of the model was also carried out by visual inspection of the hydrographs. The calibration of the model is conducted by a trial and error procedure in which the influence of the different parameters is analyzed after several simulations and parameters were set differently before the following simulation until results are sufficiently close to observed data.

5.1.2 Description of catchment.

The study area of model 1 has a size of 2800 Km². The rivers included in the hydrological model are the San Javier, Tlalnepantla, Hondo, Tacubaya, Mixcoac, Piedad and Magdalena, and the channels included are the Grand Canal, the National Canal, and the Remedios Canal. Figure 5.4 shows the Mexico City catchment, its location in Mexico and the river network.

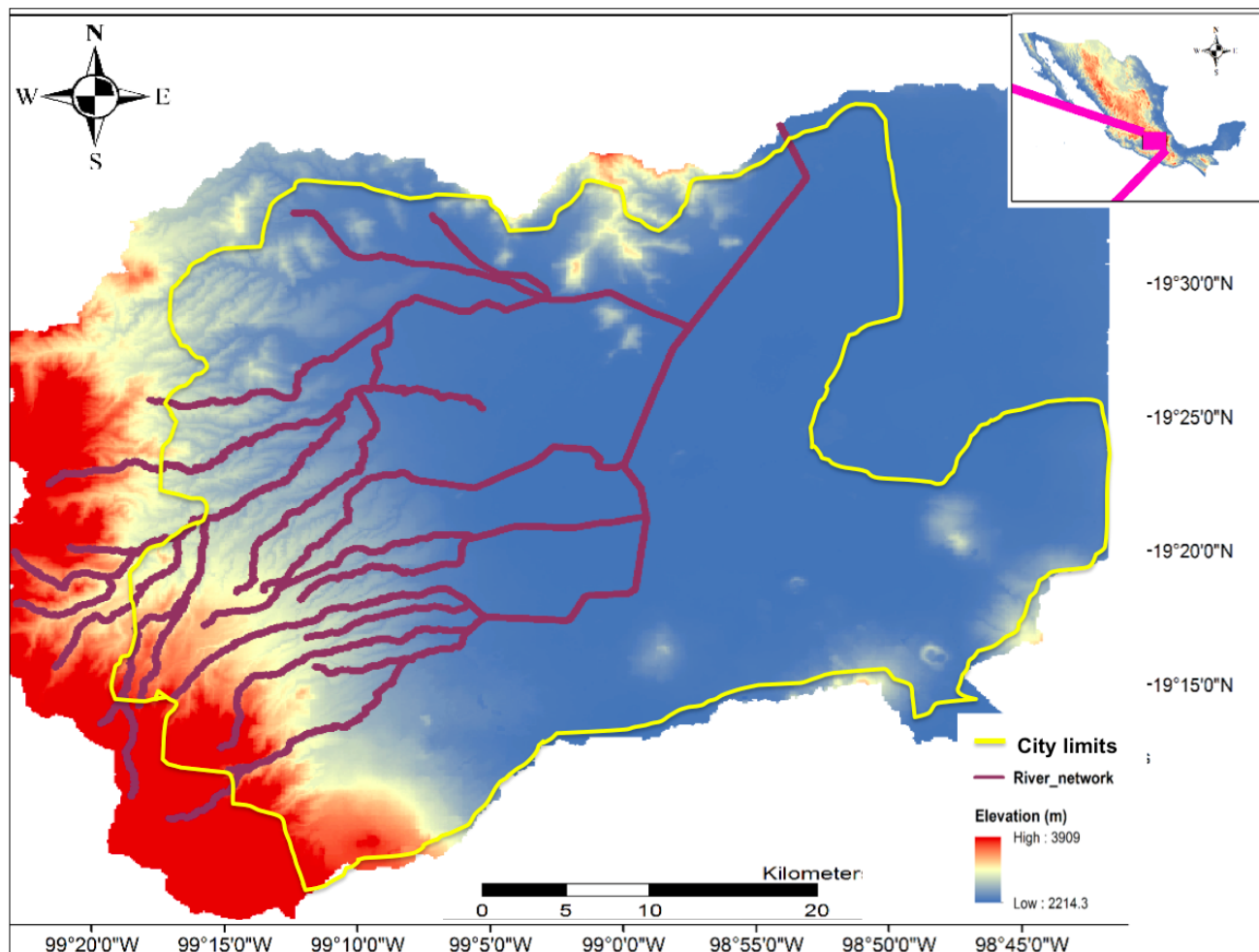


Figure 5.4 The Mexico City catchment, its location in the country of Mexico, the river network and the city limits.

Furthermore, the area of study in models 2 and 3 covers 173 Km² and includes the sub-catchment of River Hondo as shown in figure 5.5

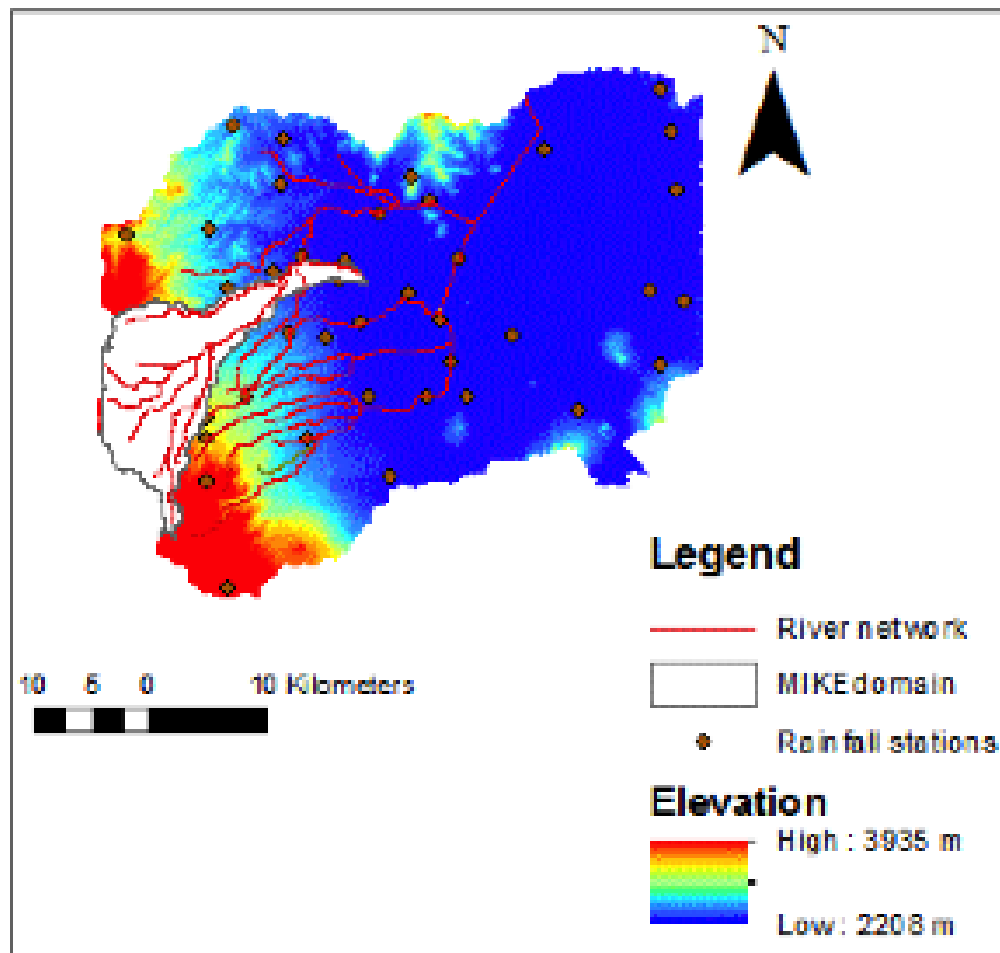


Figure 5.5 The Hondo River sub-catchment in the Mexico City catchment in white.

A MIKE SHE model for the Mexico City catchment was created. The components of the model are the following:

- Topography: The digital elevation model has a resolution of 5 meters. To speed up the simulations, a 90 meters resolution version of the DEM was generated and used in the topography component of MIKE SHE for the first number of simulations.
- Precipitation & evaporation rates: Historical observed precipitation and evaporation data from 44 stations in the Valley of Mexico were obtained from the surface waters division of the National Water Commission (CONAGUA).

Furthermore, the spatial variation of rainfall has an important effect on both runoff generation and hydrologic process in a catchment (Moon et al., 2004). The spatial variability of rainfall may introduce significant uncertainties during the calibration process [Chaubey et al., 1999]. Several studies suggest a minimum number of rainfall stations per

square kilometer. For example, Segond et al, (2007) recommends that a network of 16 rain gauges is acceptable for every 1000 km².

Therefore, for a catchment of 2,800 km², a number of 44 stations would be considered acceptable. In order to distribute the rainfall over the catchment the Thiessen method was used.

- River network: The hydrographic river network consists of a linear shape file system. A network file was completed in MIKE 11 and 27 branches were included.
- Daily average observed discharge data were obtained for 11 stations for the year of 1981 and compared with simulated discharges.
- The unsaturated zone (UZ) component, including physical and hydraulic characteristics of the types of soils. The 2-layer set-up was chosen in MIKE SHE for the unsaturated zone, and 6 types of soils were included for the soil type distribution. The data was obtained from the National Institute of geography and statistics (INEGI) and is shown in figure 5.6.

The values necessary for the MIKE SHE unsaturated zone module, such as permeability of soils, water content and hydraulic conductivity were also included.

A simulation period of 1 year was used (1981). This year was chosen because the data were available for all rainfall and gauging stations without any missing days of data, compared to other years in recent history.

Moreover, the observed discharge data available is not complete for more years before or after 1981.

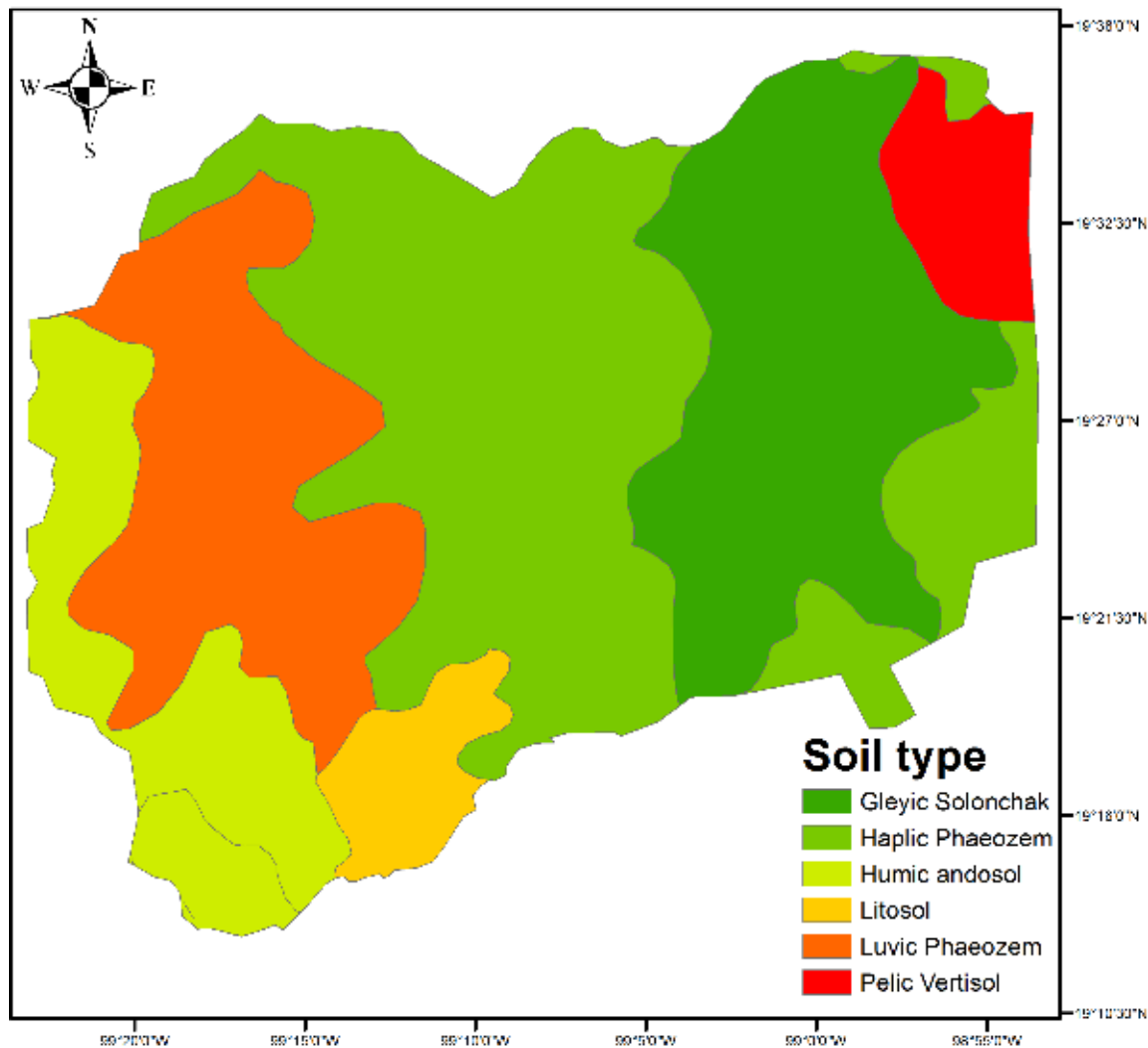


Figure 5.6 Distribution of the types of soils used in the hydrological model.

5.1.3 Application to Mexico City Basin.

The analysis is focused on the local flood problems in the the rivers Magdalena, San Javier, Piedad, Tlalnepantla, Mixcoac, Tacubaya and Hondo, where urban growth has caused an increase in runoff and discharges to the rivers. The analysis concerns also the low areas where the discharges accumulate naturally, especially when the drainage network is working at maximum capacity.

The methodology proposed was applied to the three models described. In this section, the characteristics of the catchment are described, the available data are listed, the development of each model is explained in detail and the results of the simulations are presented.

As mentioned above, the rivers modeled in are the San Javier, Tlalnepantla, Hondo, Tacubaya, Mixcoac, Piedad and Magdalena, and the channels included are the Great Channel, the National canal, and the Remedios. Only the rivers in the West of the City were modeled because these supply the largest part of the discharge to the Valley of Mexico; especially the Magdalena, Mixcoac, Hondo and Tacubaya. Figure 5.7 shows the Mexico City catchment, and the hydro meteorological network.

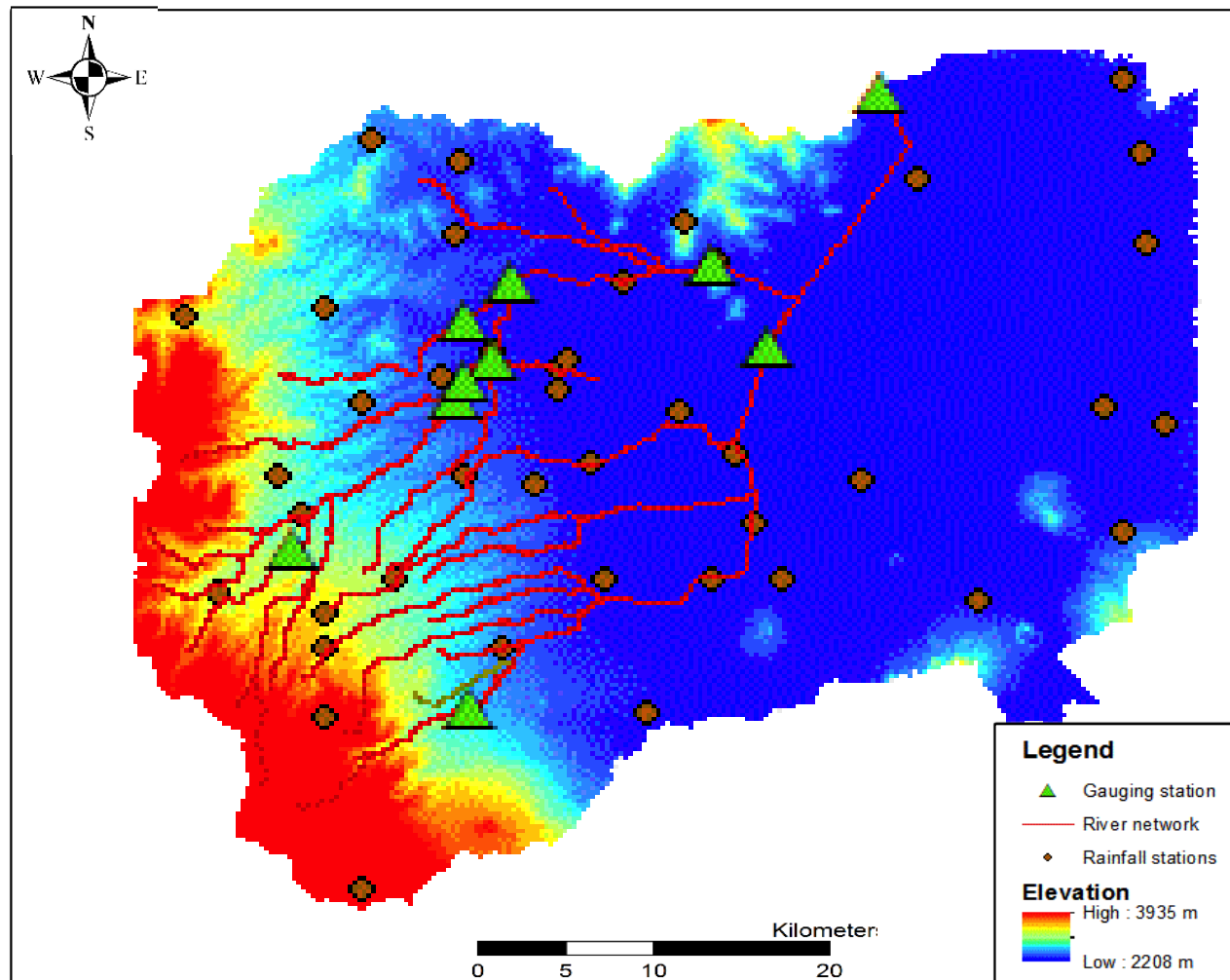


Figure 5.7 The Mexico City catchment and the hydro meteorological network.

5.1.4 Development of 3 study cases.

a. Case 1:

A model for the Mexico City catchment was created .The components include the following:

- Topography: The digital elevation model has a resolution of 5 meters. To speed up the simulations, a 90 meters resolution version of the DEM associated with a projection in UTM zone 14N was generated and used in the topography component of MIKE SHE. It should be noted that the geometry of the catchment is the most important factor in a model, and a good quality DEM can assure a good representation of the hydrological processes.
- Precipitation & evaporation rates: Historical observed precipitation and evaporation data from 44 stations in the Valley of Mexico were obtained from the surface waters division of the National Water Commission (CONAGUA). In order to distribute the rainfall over the catchment the Thiessen approach has been used. The Thiessen polygons were generated in GIS from the point shape file of the stations. The polygons were added to MIKE SHE model in order to define the precipitation spatial distribution. Several studies suggest a minimum number of rainfall stations per square kilometer. For example, Segond et. Al (2007) recommends that for largely rural catchments a network of 16 rain gauges is acceptable for 1000 km², and between 4 and 7 stations for 80-280 km². Figure 5.8 shows the rainfall distribution for the 44 stations in the Mexico City climatological network. The gauging station density is considered acceptable for the use of the Thiessen polygon distribution method. This method consists of drawing a polygon around each gauge with the boundaries at a distance halfway between gauge pairs.

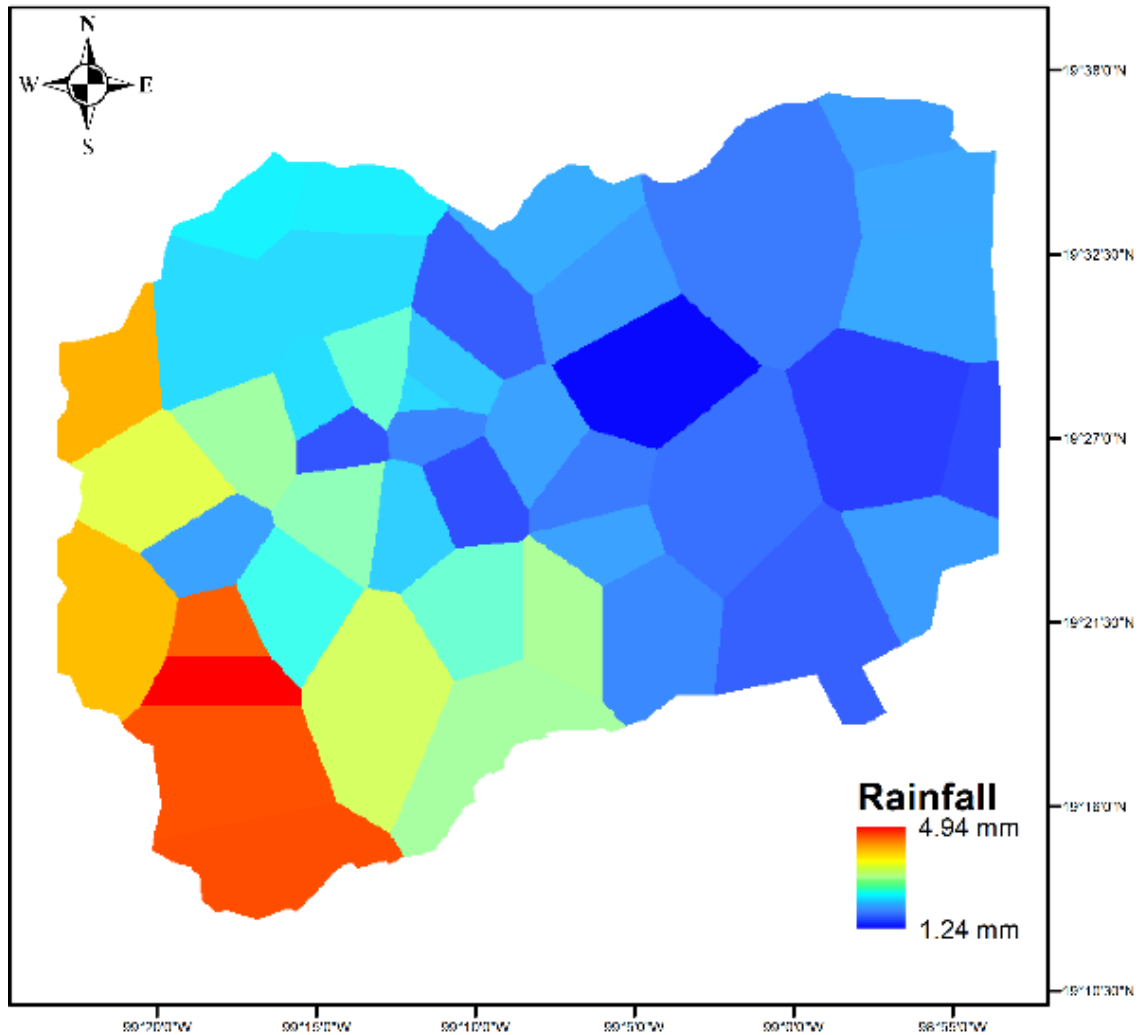


Figure 5.8 Thiessen polygon distribution and average daily rainfall for 44 climatological stations in the Mexico City catchment.

- River network: The hydrographic river network consists of a linear shape file system.
- Cross sections: Cross sections: The cross sections were obtained from the DEM using the River Bathymetry Toolkit of HEC- RAS and exported to the cross section editor in MIKE 11. In addition, one cross section was created for every 1000 meters approximately. The U.S. Army Corps of Engineers (USACE) created HEC- RAS; specifically the Hydrologic Engineering Center (CEIWR-HEC), formed in 1964 to institutionalize the technical expertise that subsequently became known as hydrologic engineering.

- Daily average observed discharge data were obtained for 11 stations for the year of 1981 and used to create time series and compared with simulated discharges.
- At the initial stage, discharge boundary conditions were set to 0.1 m³/s in all river upstream ends to avoid the initial drying of the bed.
- The water level boundary was set to a constant value in the outlet of the Great Channel based on the bed level.
- A uniform Strickler roughness value of 20 was used for the overland component of MIKE SHE, and a uniform value of 30 for all riverbeds, defined in the hydrodynamic module of MIKE 11.

b. Case 2.

For the second case study of the Hondo catchment, a model of Hondo sub-catchment was constructed including river network, rainfall, topography, and a map of distribution of the Strickler number based on vegetation data. The figure 5.9 shows the location of the River Hondo sub-catchment in the catchment of Mexico City and the hydro meteorological network is shown in figure 5.10. The model area is 173 km².

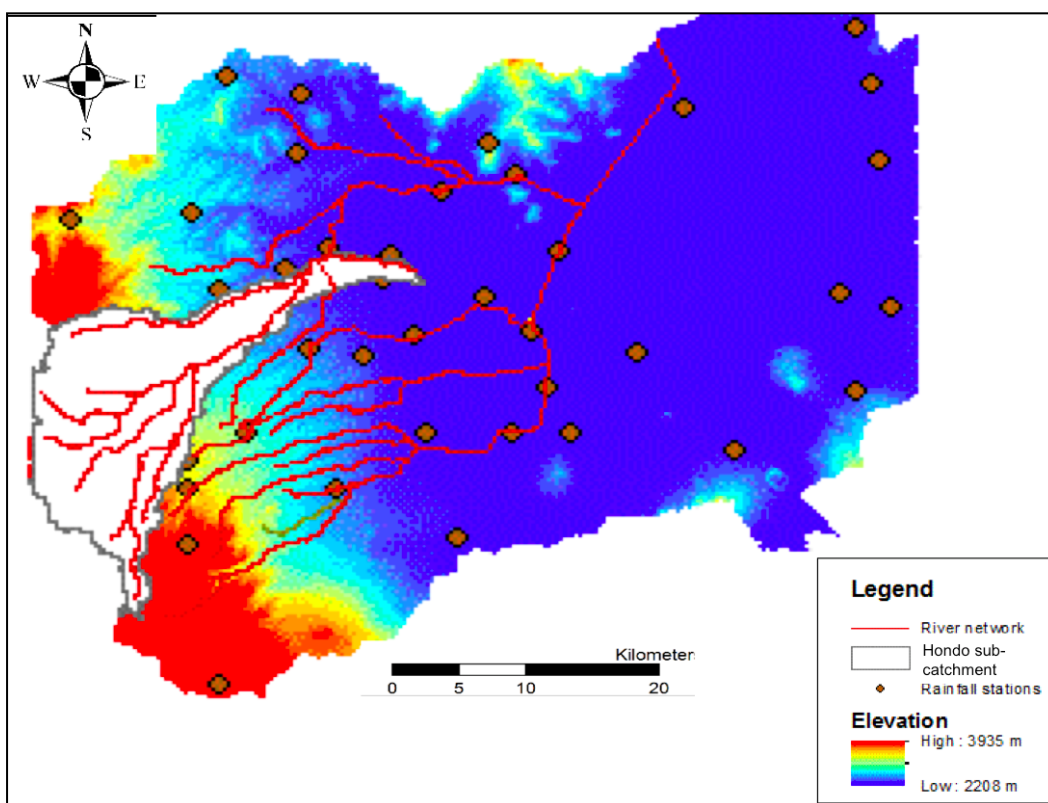


Figure 5.9 Location of Hondo sub-catchment in the Mexico City catchment

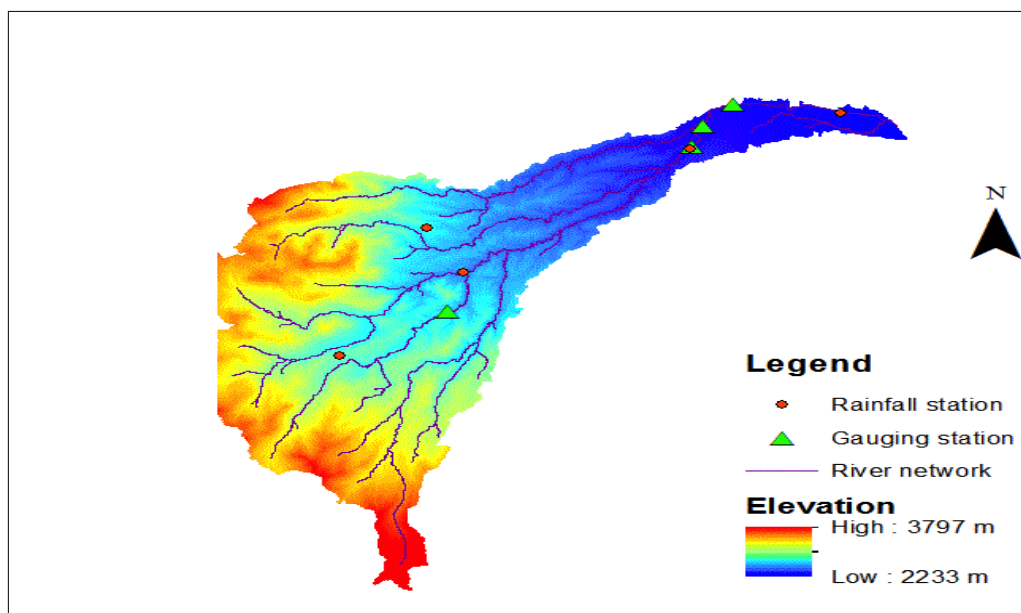


Figure 5.10 River Hondo sub-catchment with hydro-meteorological network.

Furthermore, in the second model, the Strickler coefficients have been distributed over the Hondo river basin according to the vegetation types. The overall distribution is presented

Chapter 5 – The Modeling Approach: Strategy, Data And Application

on the figure 5.11. Strickler coefficients, also known as Manning roughness coefficients, were obtained from the 'Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains', prepared by the U.S. Department of the interior, Geological survey (1989).

In addition, five rainfall stations were used for the Hondo model, and Thiessen polygons were created in GIS and added to MIKE SHE. The used rainfall distribution is shown on figure 5.12. The model was applied for the same period as in model 1 (the year of 1981), and the resulting hydrograph was compared to observed values in Molino Blanco station.

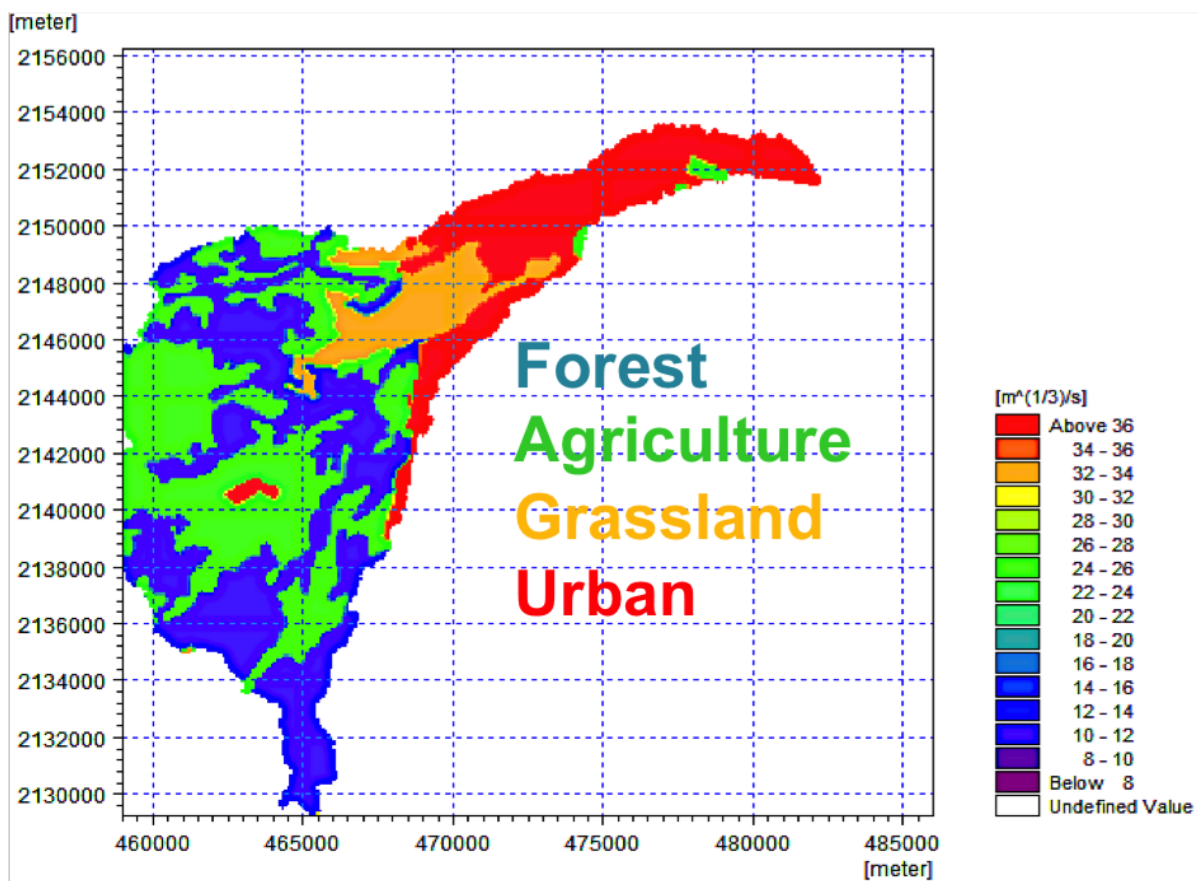


Figure 5.11 Distribution of Strickler coefficient in Hondo catchment according to land use.

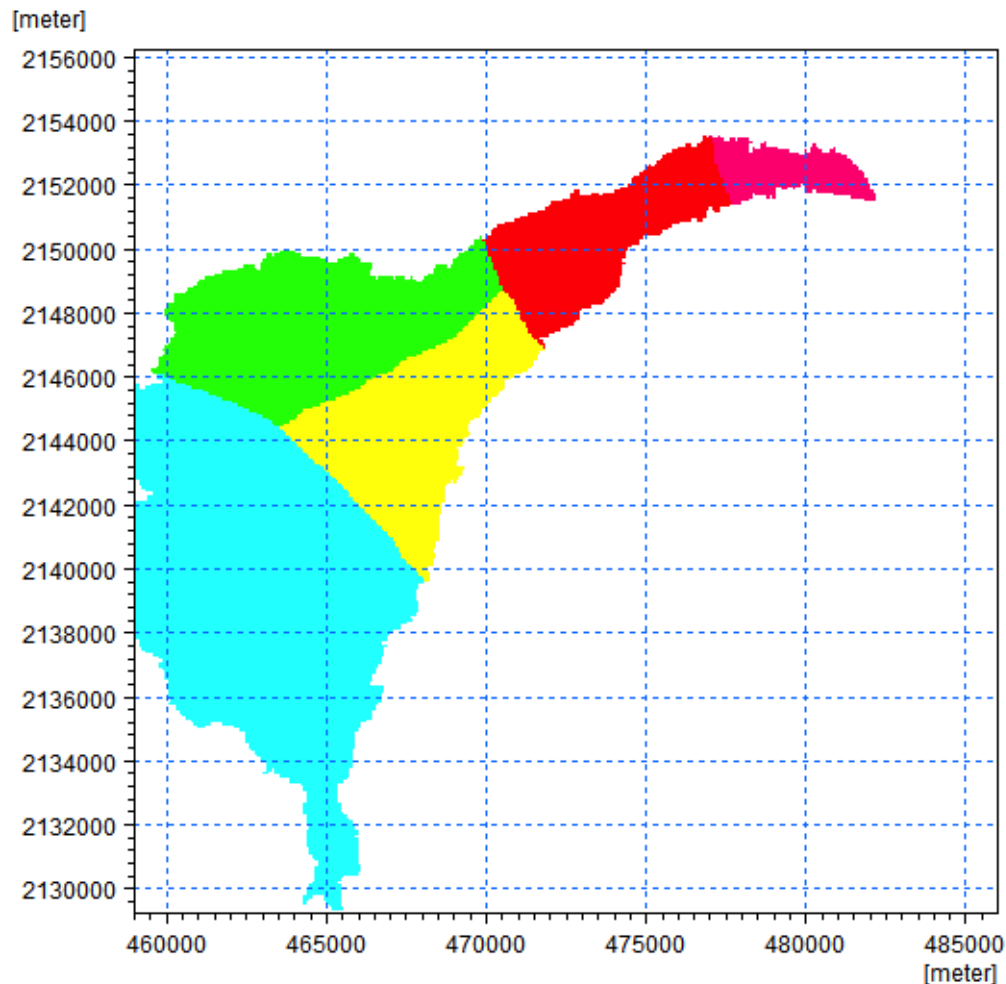


Figure 5.12 Thiessen polygon rainfall distribution of 5 stations in Hondo River sub-catchment.

c. Case 3:

For the third study case of the Hondo catchment, the unsaturated zone (UZ), evaporation and land use components of MIKE SHE were included in addition to the same Strickler number distribution. The used rainfall distribution for case 3 is the same as in case 2. The land use information was extracted from digital maps and added to the land use module of the model. The 2-layer set-up was chosen in MIKE SHE for the unsaturated zone, and 6 types of soils were included in this set-up. The soil type polygons were obtained from INEGI.

According to the MIKE SHE reference guide (2007), the Two-Layer Water Balance Method is an alternative to the more complex unsaturated flow process coupled to the Kristensen and Jensen module for describing evapotranspiration. The main purpose of the module is to calculate actual evapotranspiration and the amount of water that recharges the

saturated zone. The module includes the processes of interception, ponding, infiltration, evapotranspiration and ground water recharge. Furthermore, while MIKE SHE's unsaturated zone module requires a detailed vertical discretisation of the soil profile (unsaturated zone), the simplified ET module considers the entire unsaturated zone to consist of two 'layers' representing average conditions in the unsaturated zone. The input for the model includes the characterisation of the land use and the physical soil properties.

Other values necessary for the MIKE SHE modules of land use and unsaturated zone, include permeability of soils, leaf area index of vegetation, root depth, Strickler coefficients, water content and hydraulic conductivity of soils. Figure 5.13 shows the soil types boundaries.

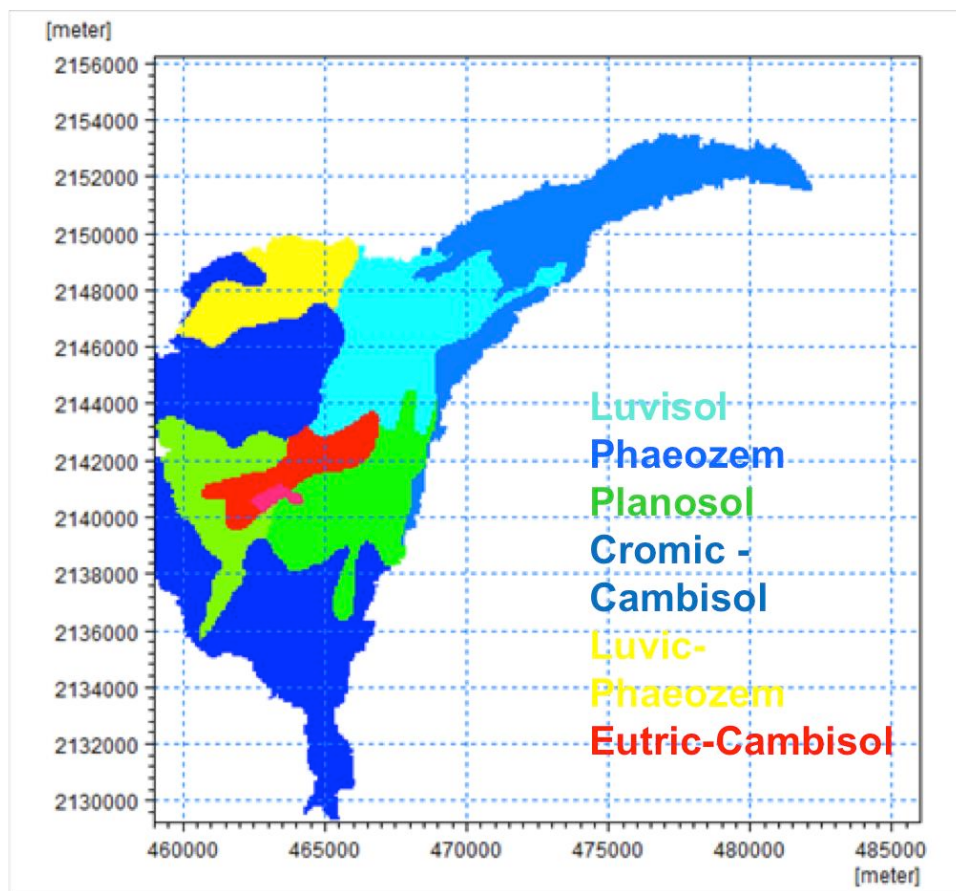


Figure 5.13 Boundaries of the 6 different types of soils used in the River Hondo set-up.

Chapter 5 – The Modeling Approach: Strategy, Data And Application

For all cases, a period of 1 year was chosen (1981) because data were available for all rainfall and gauging stations in this year. The simulation time step was 10 seconds in MIKE 11 (hydraulic component of Mike She).

The time step control values used, necessary to control the simulation in MIKE SHE, are listed below.

Initial time step	6 hrs
Max allowed overland time step	12 hrs
Max allowed UZ time step	24 hrs
Increment of reduced time step length.	0.05
Max precipitation depth per time step	20 mm
Max infiltration amount per time step	10 mm
Input precipitation rate requiring own time step	1 mm/hr

Table 5.1 Values for the control of time steps during the MIKE SHE simulation.

The setup of the three study cases was successful and a series of simulations was done to calibrate the model. The purpose of calibration is to confirm that the model is able to reproduce the hydrological processes with reasonable accuracy. However, it is a complex procedure due to the large amount of model parameters involved, and the computational requirements for simulations.

Therefore, calibration is considered one of the most time consuming phases when building a hydrological model. (Vazquez et al, 2002). The model was calibrated for one year (1981); however, the land use data provided by INEGI was generated in 2009, which presents a considerable difference with the land use distribution of 1981, due to the urban development in the last decades. However, as the land use data (from INEGI) is not available for 1981, we can only wait for the discharge and rainfall data of 2009 (or close to this year to be available).

A series of simulations was carried out to calibrate each of the three models. In this research, calibration was done through trial and error, where a variable was changed at a time before every simulation, until the desired results was obtained. The parameters calibrated in this study were the simulation time step and the discharge boundary conditions in the upstream initial points of each one of the rivers. It should be noted that several hydro-informatic issues were faced during simulation. Several errors and warnings

when running MIKE 11. For example, warning 65 about abrupt changes in the river elevation, and warning 47 which notifies about the drying of the riverbed. The river elevation can be adjusted using the cross section editor, and determining a constant flow in the inlet of the river branch can solve the drying of the riverbed. Warnings do not prevent the model from running after coupling with MIKE SHE, however, they can cause errors that cause the simulation to stop.

Furthermore, the time of simulation was considerably high due to the DEM grid size, and it was therefore decided to increase the grid size from 5 m to 90 m for the first simulations. The original grid size was restored after calibration. However, the issue that took the most time to resolve in this study was error 25 of MIKE 11. This error occurs when, at a certain point, the water depth is greater than the maximum allowed depth by a factor of four. It was found that increasing the allowed factor for exceedance in the Mike11.ini file was the best solution as suggested by the DHI user guide for this issue.

5.1.5 Results

The predictive capability of the model set-up was evaluated by comparing the resulting hydrographs against independent observed data. The results of the three cases described in the methodology are presented in the following paragraphs.

a. Case 1:

The model of Mexico City catchment includes topography, rainfall and river network. Figure 5.14 and figure 5.15 show the resulting hydrographs from the simulation of the Mexico City catchment model compared with observed values for Molino Blanco stations in river Hondo and St. Teresa station in river Magdalena respectively. The resulting RMSE and E values can be seen in table 5.2. The E coefficient in the St. Teresa station was a rather low -0.03, and the RMSE was 2, which can be considered high. Furthermore, in the Molino Blanco station, the E coefficient was a reasonable 0.73, and a rather high 3.34 RMSE was obtained.

	St. Teresa	Molino Blanco
RMSE	2	3.34
E	-0.03	0.73

Table 5.2 Statistical coefficients of the MIKE SHE model of Mexico City catchment.

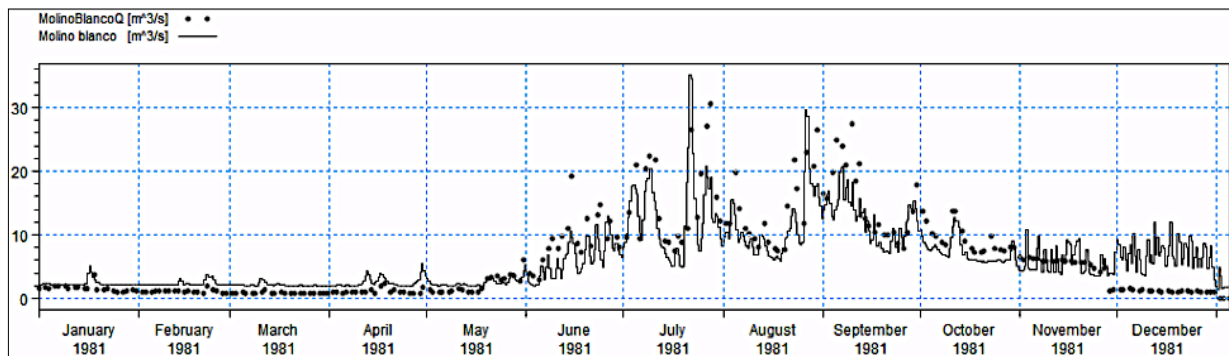


Figure 5.14 Molino Blanco station simulated discharge against observed discharge for the Mexico City catchment model (1981).

In the Molino Blanco station, the resulting hydrograph is remarkably close to the observed data, however, there are important discrepancies in the months of June, July, August and September. Also during December, the model did not stabilize. This may be caused by different factors and all the variables in the model should be carefully analyzed to determine their influence on the result.

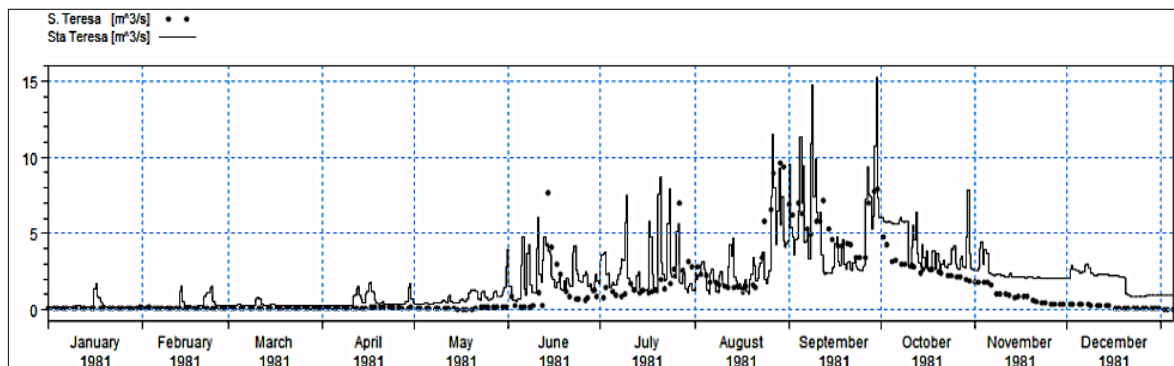


Figure 5.15 St. Teresa station simulated discharge against observed discharge for the Mexico City catchment model (1981)

In St. Teresa station, the results follow successfully the main processes and trends but the model doesn't succeed to present properly the intensity of several flood events appearing during September and October in the Magdalena River. The representation of the processes in this model may be too coarse, and do not integrate enough variables for representing the hydrological behavior of the catchment.

b. Case 2:

For the model of the Hondo river sub-catchment, the Strickler coefficients have been distributed over the basin according to the vegetation types. This model was applied for the

same period as case 1 and the resulting hydrograph was compared to observed values in Molino Blanco station. The hydrograph can be seen in figure 5.16. The model produced a value of 0.71 for the E coefficient and 3.48 for the RMSE coefficient.

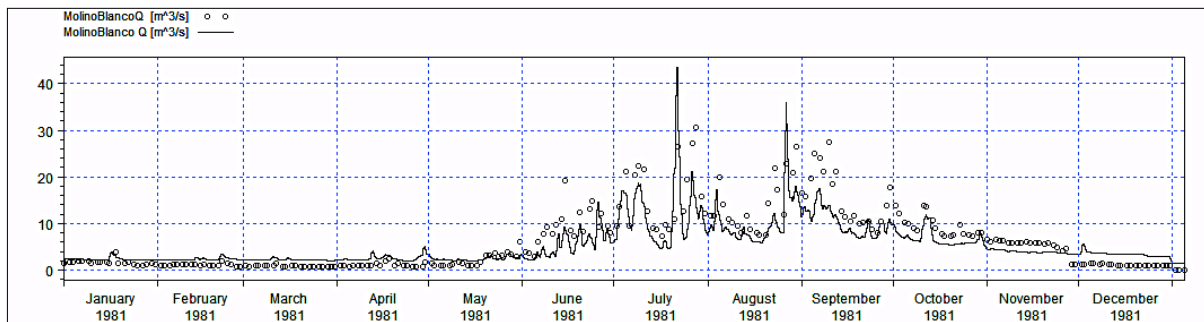


Figure 5.16 Molino Blanco simulated discharge against observed discharge Hondo sub-catchment model including the effects of vegetation in Strickler coefficient (1981).

The results of case 2 followed relatively well the main trends of the observed data, and it stabilized well in the month of December. However, this model has a consistent difference between the gauged data, especially from July to September.

c. Case 3:

The third model includes the land use data and the unsaturated zone data. The results obtained are a rather high RMSE of 3.05 and and a reasonable E coefficient of 0.77. Figure 12 depicts simulated discharges in the Molino Blanco gauging station compared to observed values. The figure 5.17 represents simulated discharges in Molino Blanco gauging station compared to observed values.

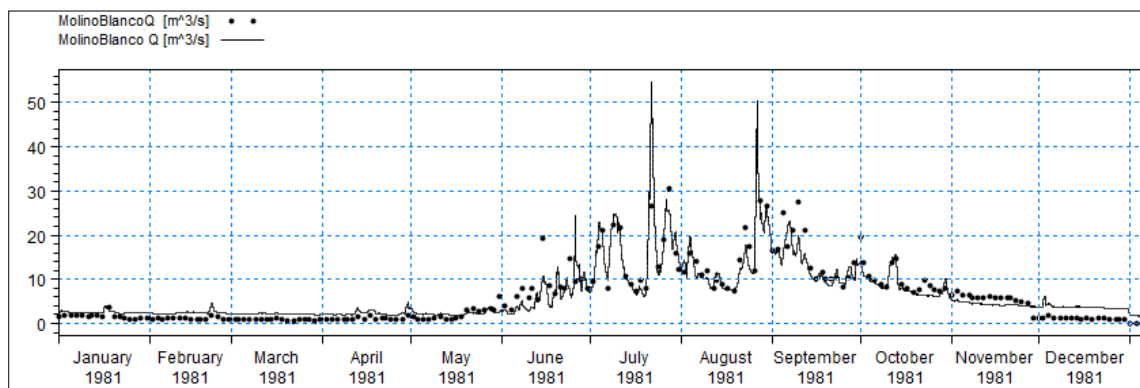


Figure 5.17 Molino Blanco station simulated discharge against observed discharge in Hondo River catchment model with unsaturated zone and land use components (1981).

The results of model 3 follow the main trends of the observed data. According to the hydrograph, it can be stated that the effects of the soil types and the land use data provide a benefit for the representation of the hydrological process in the catchment compared to the first two models; however, an important difference can be observed in July and August, when an excessive amount of simulated discharge appears.

It should be noted that even when the results of the MIKE SHE model regarding discharge in the rivers are satisfactory, the simulation period of one year limits the understanding of the behavior of the catchment during a longer period. Therefore, it is recommended to do a longer period of simulation in order to verify the applicability of the model.

Therefore, a simulation with a period of 5 years was carried out including the unsaturated zone component and land use, and the resulting hydrograph is shown in figure 5.18.

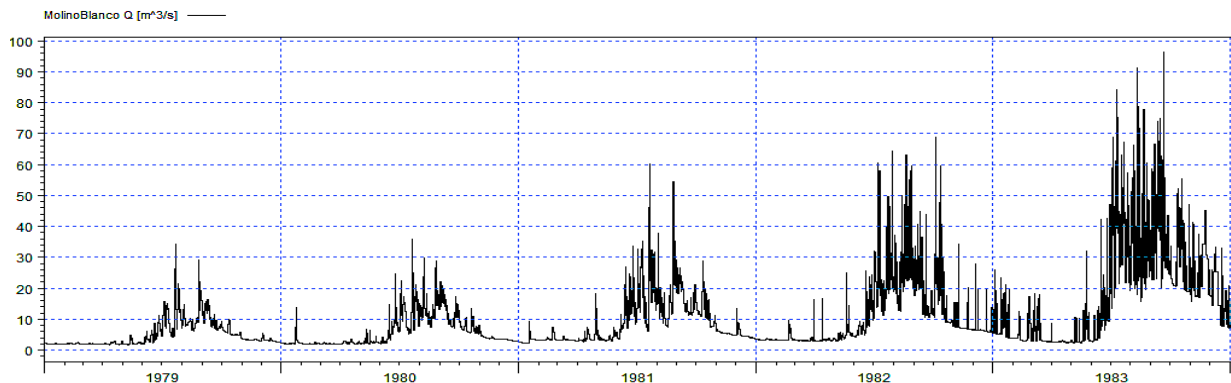


Figure 5.18 Molino Blanco station simulated discharge in Hondo River catchment model with unsaturated zone and land use components for a period of 5 years.

As the observed discharge is not available for these years; because no data was collected or it has not been captured or published yet, the hydrograph shows only the simulated discharge. However, the water commission (CNA) recorded the date and times of the maximum discharge for each month during this 5-year period; and this information was used to analyse the hydrograph. The hydrograph presents an obvious increment of discharge for each year.

To analyse the simulated discharge, the recorded peak discharge was used to compare with the simulated discharges. The date and the flow magnitudes of the two maximum discharges recorded in Molino Blanco station are presented in table 5.3.

	Peak discharges River Hondo Molino Blanco station (m^3 / s)			
	Observed		Simulated	
	Date/time	Magnitude	Date/Time	Magnitude
1979	26-Jul 15:00	21	22-Jul 01:00	35
	28-Aug 23:00	20	27-Aug 04:00	29
1980	13-aug 15:00	15	21-Jul 01:00	38
	3-Sep 21:00	18	07-Aug 21:00	30
1981	8-Jul 17:00	28	20-Jul 18:00	80
	27-Aug 20:00	40	27-Aug 08:00	77
1982	03-Aug 17:00	20	10-Jul 10:00	114
	18-Aug 18:00	16	05-Oct 2:00	130
1983	12_Jul 17:00	29	06-Aug 16:00	170
	18-Jul 18:00	26	11-Aug 5:00	223

Table 5.3 Maximum discharges recorded for Molino Blanco station in the 1979-1983 period and maximum discharge simulated.

The maximum simulated discharges were all obtained during the rainy season from June to September in the 5 years, and discharge decreased during the dry season as it occurs in reality. However, it can be inferred from the table that simulated discharge increased abnormally compared to maximum discharge observed from 1979 to 1983. This should be investigated and carry out a proper calibration.

5.2 Flood hazard mapping with 2D hydraulic modeling

In this section, a method for flood map creation using MIKE 21 software is proposed to assist in flood risk management in the basin of Mexico City. The Université de Nice Sophia Antipolis provided this software.

DHI Water and Environment's MIKE 21 two-dimensional modeling system has been one of the leading models used in full two-dimensional flood analysis in several countries. Over the years a number of improvements of MIKE 21 have enhanced its ability to model floodplain flows. (McOwan et al, 2001). Due to these improvements, MIKE 21 has been applied in recent years in several flood hazard studies worldwide. For example, Chandra and Ahsan (2009), carried out a rapid flood hazard assessment using MIKE 21 2D hydrodynamic model.

In a more recent study, Filipova et al. (2012) created a two-dimensional hydrodynamic simulation model using MIKE 21, developed as a tool to simulate storm water related flooding in the central part of Gothenburg, Sweden. These recent studies suggest that flood hazard assessments using MIKE 21 have a reduced cost, provide an understanding of flood risk areas more rapidly than conventional studies and allow flood risk studies in urban catchments.

The analysis in the present work is focused on the flood problems in the high surrounding areas of the West part of the City, and low areas where the discharges accumulate in artificial channels, especially when the drainage network is working at maximum capacity.

5.2.1 Application of MIKE 21.

For this model, a bathymetry with an area of 980 km² was used. This area covers only the downstream area of the catchment because the focus was on the area where the flooding events of the highest magnitude occur; as opposed to the area of study in the MIKE SHE hydrological model (2.800 km²), in which our focus was on simulating runoff from the several rivers.

The components to construct the MIKE 21 model are:

- Topographical data covering the floodplain area of Mexico City were the most severe and frequent flooding events occur. The bathymetry resolution used was 30 meters.
- Boundaries obtained from the time series of discharge of MIKE SHE hydrological model for 7 rivers, and a time series of water level for the outlet of the river network.

- Rainfall time series and Thiessen polygons distribution for the simulation period and for the 44 rainfall stations.

The method applied for the generation of flood maps is the following:

- Generate discharge hydrographs using MIKE 11 for the main rivers of the West of the catchment of Mexico City, and the water level time series for the downstream end of the network. The discharge was calculated in locations of each river selected previously based on the points corresponding to the upstream ends of the MIKE 21 model network, including: San Javier (at 3.8 Km), Tlalnepantla (at 13.6 Km), Remedios (at 13 Km), Tecamachalco (at 18.8 Km), La Piedad (at 14.9 Km), Mixcoac (at 20.2 Km), San Angel (at 9.3 Km); and the water level at 18.2 Km of Gran Canal was calculated for the downstream boundary condition of the MIKE 21 model.
- Select a simulation period of 15 days from 01/09/1981 to 15/09/1981. The month of September was chosen because Mixcoac station presented the highest simulated discharge of all stations in September; above 50 m³/s. Based on the hypothesis that the flooding of highest magnitude could occur in this month, this period was used to simulate the flood depth.
- Introduce the time series of the discharge of each river as a source in MIKE 21 software and the water level time series in the location of the outlet of the catchment.
- A rainfall distribution was applied based on the Thiessen polygon method.
- Select a constant Manning value of 60 m^(1/3)/s for the resistance. This value was based on the land use of the downstream area of the catchment, consisting of urban area mostly.

5.2.2 Results.

The resulting maps of maximum water depth from the MIKE 21 simulation using topography of 50 meters and 30 meters are shown in Figure 5.19 and Figure 5.20 respectively, as well as the point where the Remedios channel and the Great channel intersect. These results suggest that the depth and the extent of flooding are dependent on the resolution of the topography. For instance, it can be seen in figure 5.120 that with a grid size of 30 m, more water flow into the rivers and channels, causing flooding in areas of the city that were not flooded when the 50 m resolution was used, such as the area around

the point of intersection between the Great channel and the Remedios channel, and causing a reduction in the flood extent in other areas.

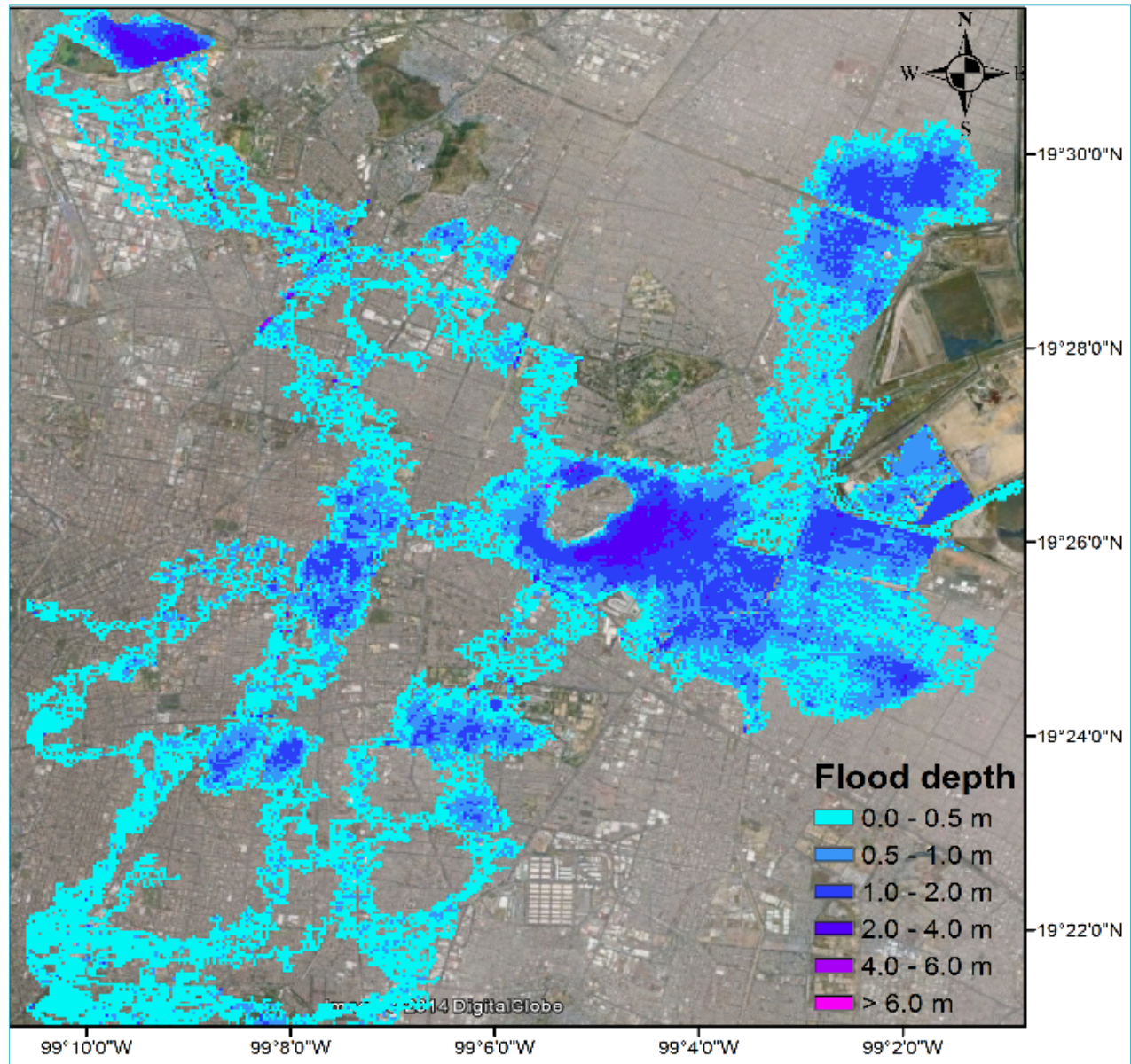


Figure 5.19 Maximum water depth using topography of 50 m of grid size.

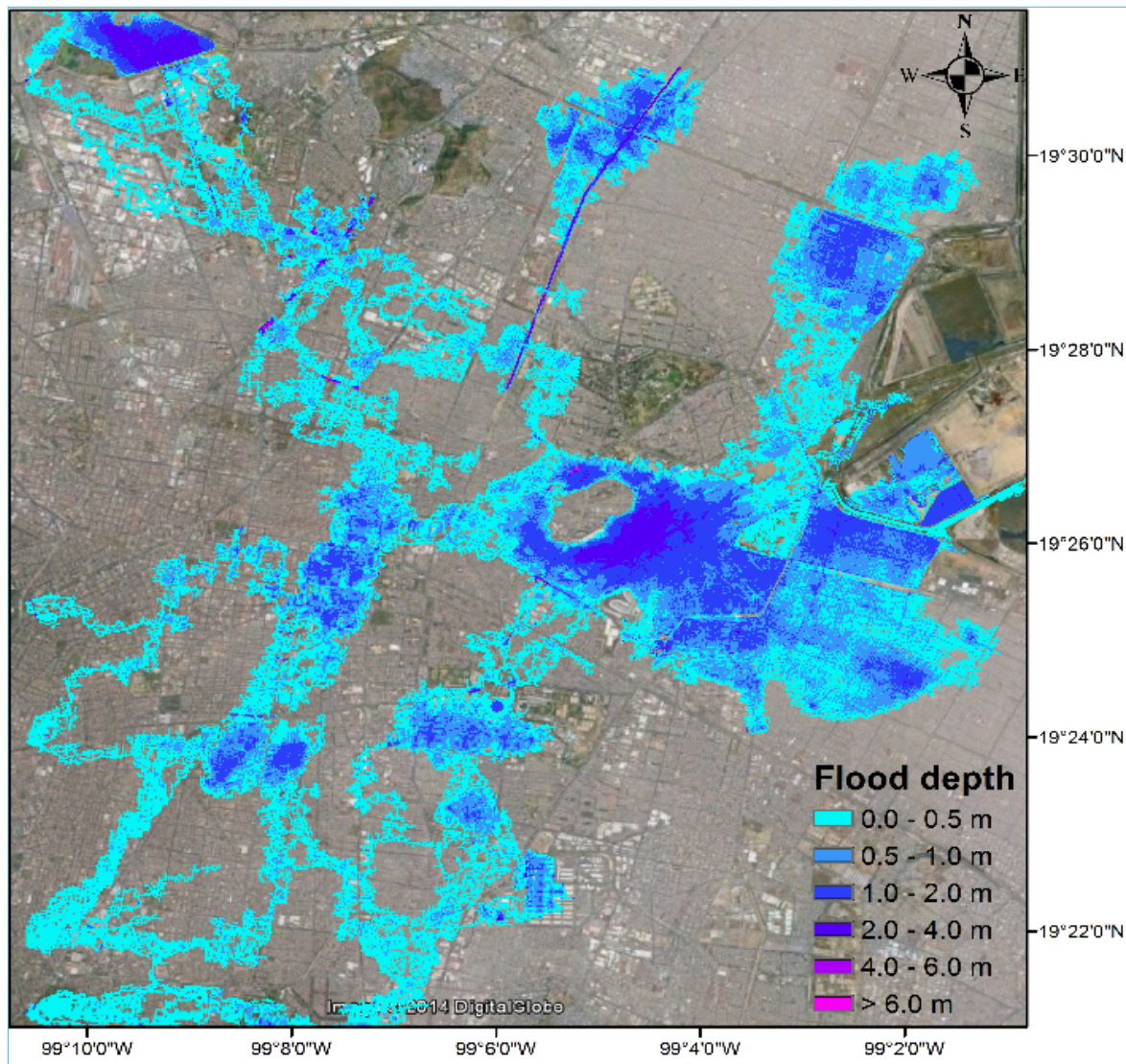


Figure 5.20 Maximum water depth using topography of 30 m of grid size.

The flood event simulated caused water depths between 0.5 and 1 meter in the areas covering the Benito Juárez international airport, the northern part of Nezahualcoyotl, Chimalhuacan, the Valley of Ecatepec, the historic center (west of the Great channel), and an area East of the Carretas reservoir in Tlalnepantla.

After obtaining the flood extent map with 30 m grid size, it can be considered that this map is sufficient to carry out the operational management of the catchment. The appropriate land use is determined based on the vulnerability to flooding of the building type or its occupational use. With the flood map obtained, the types of buildings affected can be recognized and also their number. For example, a hospital is typically considered a highly vulnerable use and, therefore, it is more appropriate to locate hospitals in areas at lower

probability of flooding. The flood map let us know what are the areas of higher flood depth, and this is useful when planning the building types in those areas.

The total flood area is expected to change when increasing the resolution of the topography, however, the general flood hazard zones can already be delimited with the flood map of 30 m grid size.

Furthermore, land use plans incorporating flood risk management through the creation of flood zones, and development frameworks that specify appropriate land use provide guidance about the type of development that can occur and where it can occur.

However, this guidance should be accompanied by regulation to legally control development. Such regulations will need to interface with existing land use control, planning and building control legislation and will be limited by the strength of current land use planning procedures. [Jha et al. 2012]

Typically regulations include:

- The appropriate uses for new development permitted in a designated zone
- The requirement for flood risk assessment for all new developments
- Minimum design standards for permitted development within a designated zone
- Compulsory drainage and surface water management plans
- Presumption against reconstruction of damaged dwellings within designated zones
- Compulsory retrofitting of flood protection measures.

Furthermore, the flood map obtained with a 30 m grid size already allows recognizing areas where structural flood control is needed. For instance, when the flood area corresponding to a flood depth above 2 meters was analyzed, the only zones that presented this flood depth are the ones covering the international airport and the area west of the Carretas reservoir (North of the Remedios channel). It should be noted that the area covering the airport is protected from flooding by the reservoirs to the East; however, the areas of flood risk to the North of the Remedios Channel in Tlalnepantla are still in need of protection from future flood events.

Therefore, it is our recommendation to construct a barrier along this channel or take other infrastructural measures in order to reduce the damage from flooding.

5.3 Topography grid size sensitivity analysis.

The discharges in 7 rivers, and the water level downstream, obtained in MIKE SHE, were input in MIKE 21 as boundaries for the model. Furthermore, these results were used in the MIKE 21 model for assessing the extent of the areas of flood risk and the flood depth in Mexico City. In addition, the effect of changing the resolution of topographic data was studied to determine the impact of DEM accuracy and case studies on the effect of resolution of topographic data are discussed. DEMs with larger grid sizes have less detailed information as they have one elevation value for a larger area. DEMs with high resolution or smaller grid sizes represent elevations of smaller areas and can better represent the smaller topographic details. Grid sizes of 50 m, 30 m and 20 m were used in MIKE 21 to create flood maps and analyze the differences in the results of flood extents and depths.

The components to construct the MIKE 21 model are:

- Topographical data covering the floodplain area of Mexico City. The bathymetry resolutions used were 50 m, 30 m, and 20 m.
- Boundaries obtained from the time series of discharge of MIKE SHE hydrological model for 7 rivers, and a time series of water level for the outlet of the river network.
- Rainfall time series and Thiessen polygons distribution for the simulation period for 44 rainfall stations.

The resulting maps of maximum water depth from the MIKE 21 simulation using topographies with grid sizes of 50 m, 30 m and 20m are shown in Figures 5.21, 5.22 and 5.23 respectively.

These results suggest that the depth and the extent of flooding are dependent on the resolution of the topography. For instance, it can be seen in figure 5.22 that with a grid size of 30 m, more water flow into the rivers and channels, causing flooding in areas of the city that were not flooded when the 50 m resolution was used; such as the area around the point of intersection between the Great channel and the Remedios channel, and reducing the flood extent in other areas.

Similarly, the flood map produced with a 20m DEM shows that with a grid size of 20 m, more water flow into the rivers and channels, causing higher flooding in some areas of the city and reducing the flood extent in other areas.

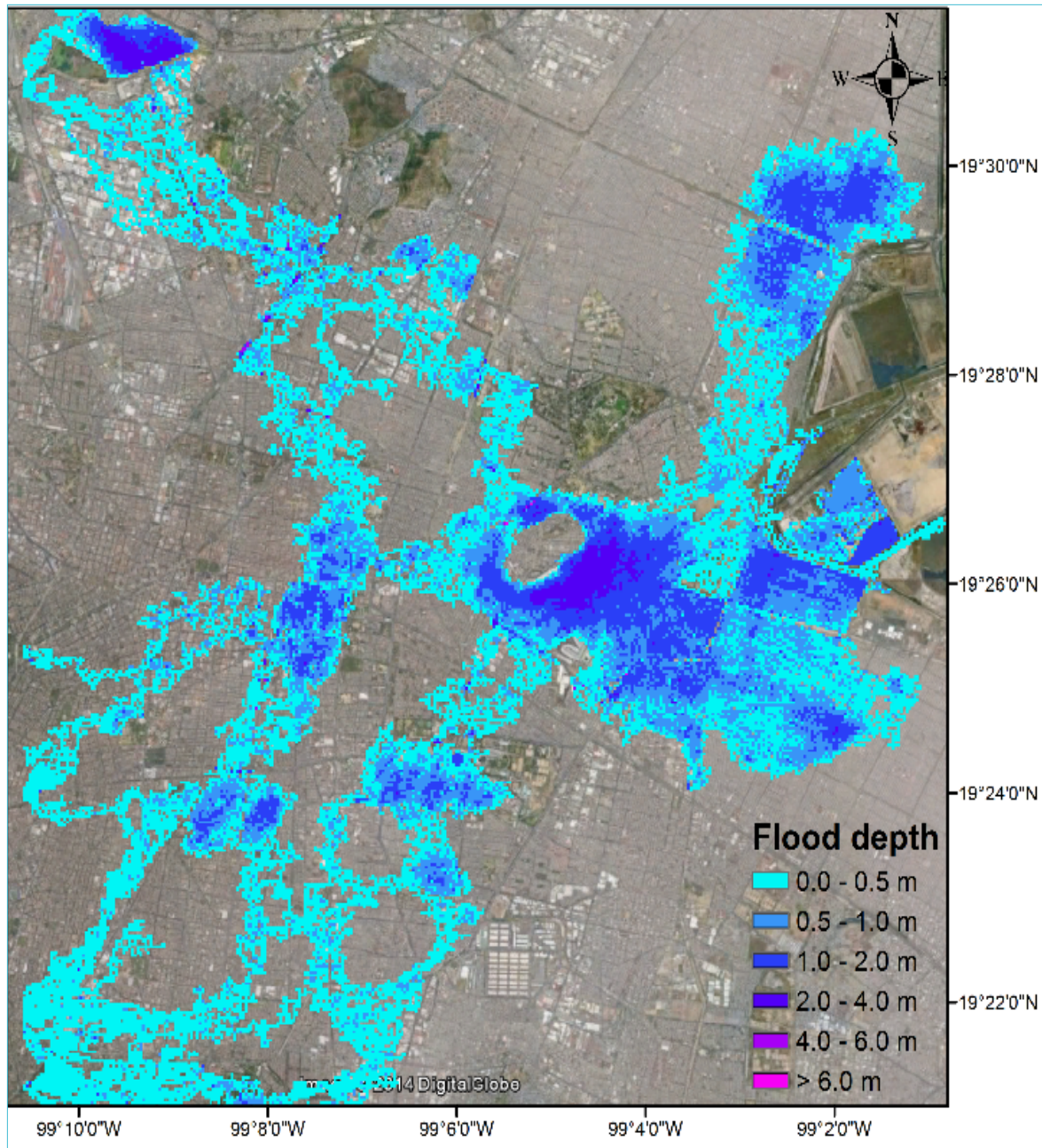


Figure 5.21 Maximum water depth using topography of 50 m grid size.

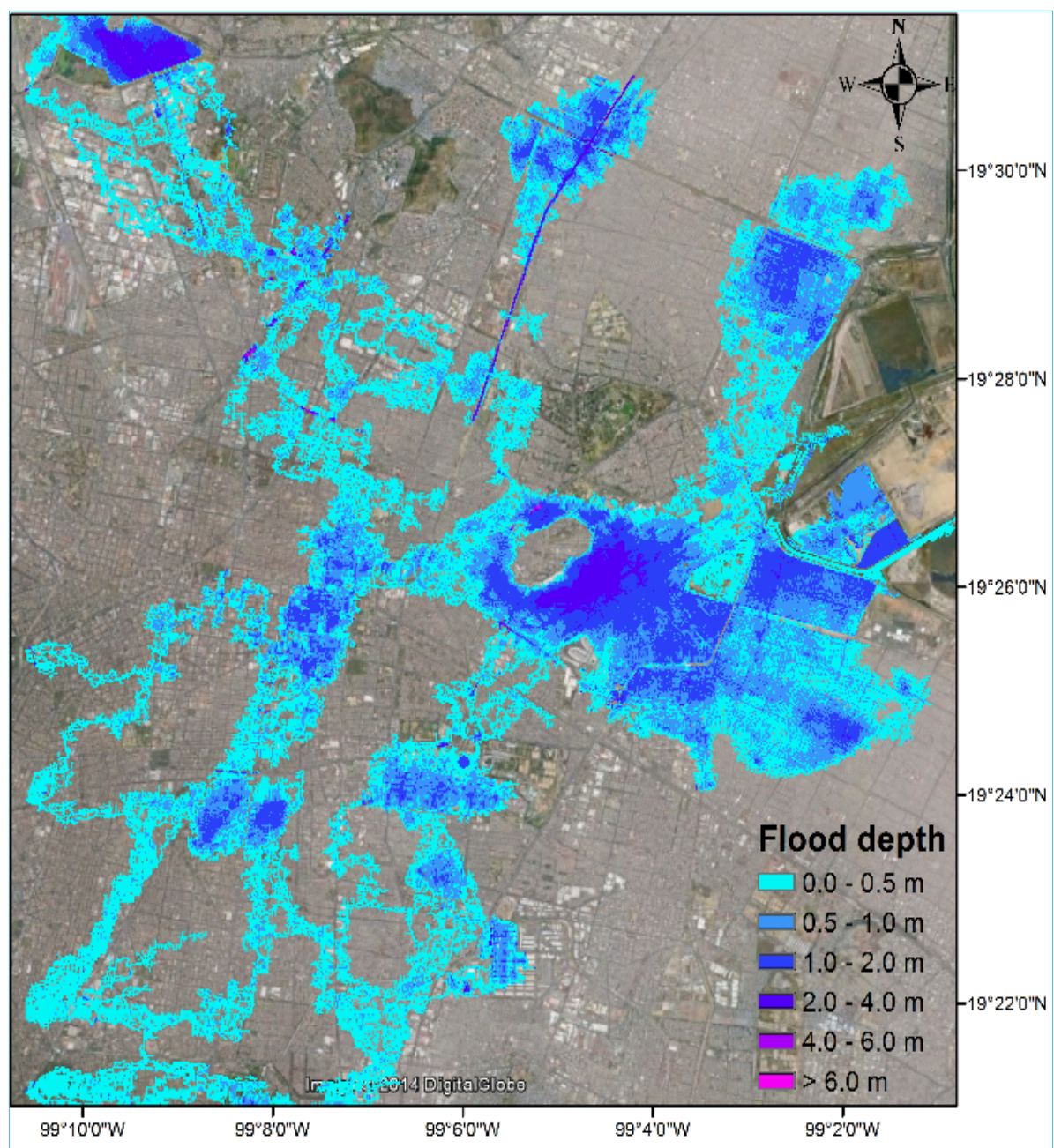


Figure 5.22 Maximum water depth using topography of 30 m grid size.

The flood depth was estimated for September in 1981, and the statistical flood area for each topographical grid size (50m, 30m and 20m) and for each flood depth interval can be found in Table 5.4

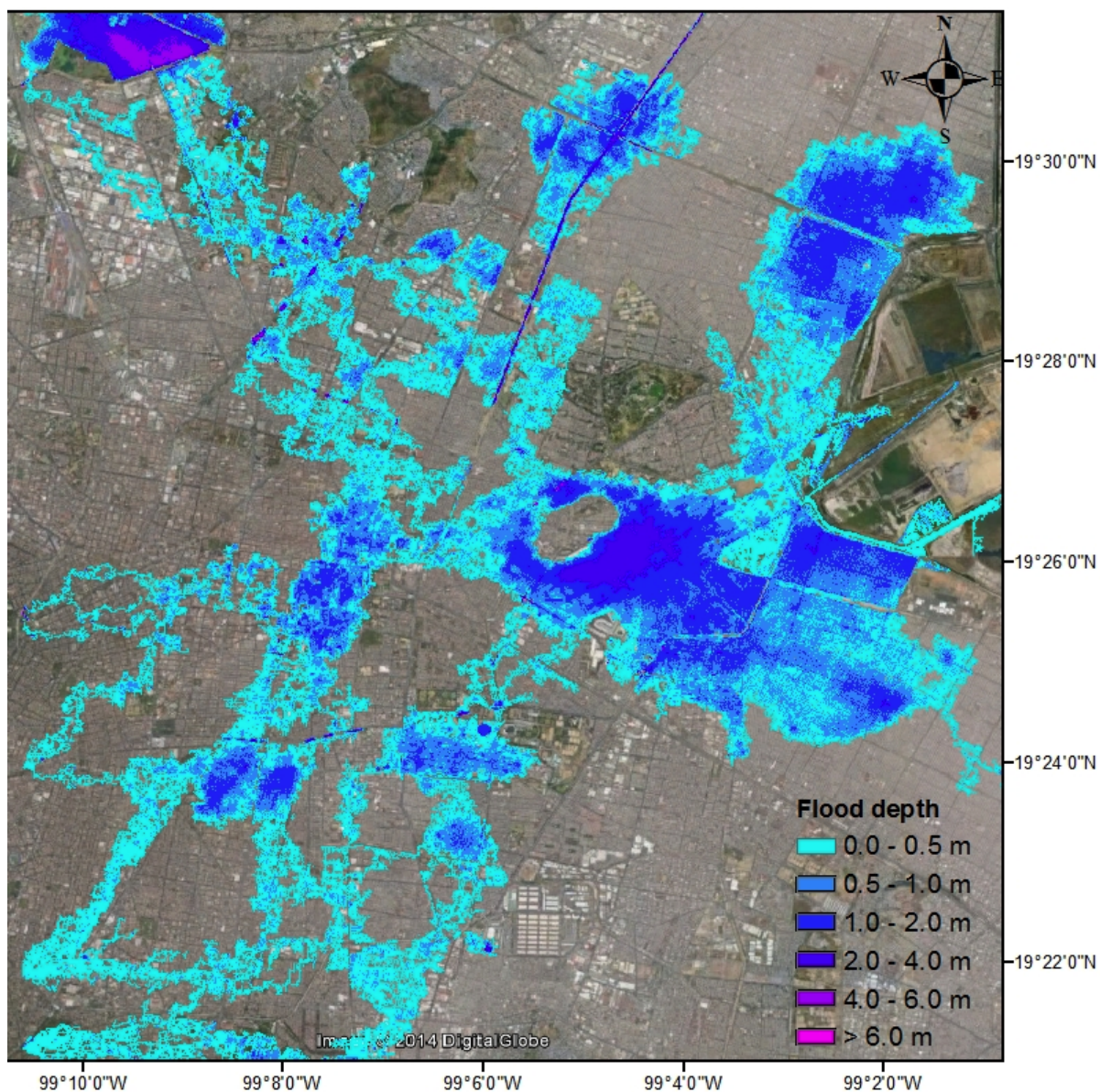


Figure 5.23 Maximum water depth using topography of 20 m grid size.

The flood event simulated caused water depths between 0.5 and more than 5 meters in the areas covering the Benito Juárez international airport, the northern part of Nezahualcoyotl, Chimalhuacan, the Valley of Ecatepec, the historic center (west of the Great channel), and an area East of the Carretas reservoir in Tlalnepantla for the three grid sizes.

Flood depth (m)	Flood area (m2)		
	50m	30m	20m
0.5 – 1.0	22,022,500.00	23,327,100.00	25,180,000.00
1.0 – 2.0	12,290,000.00	12,021,300.00	15,313,600.00
2.0 – 3.0	1,707,500.00	1,942,200.00	2,243,600.00
3.0 – 4.0	2,22,500.00	543,600.00	807,200.00
4.0 – 5.0	35,000.00	28,800.00	483,200.00
> 5.0	22,500.00	33,300.00	59,600.00
Total	36,300,000.00	37,896,300.00	44,087,200.00

Table 5.4 Statistical flood areas corresponding with flood depth and grid size for flood event of September 1981.

The analysis of total the flood extent obtained with grid sizes of 50m, 30m and 20m indicate that the flood area increased when reducing the grid size. However, the study by Haile, A., & Rientjes, T., (2005) as shown in figure 2.5 in chapter 2, found that the flood area increased when the resolution was increased from 7.5 m to 2.5 m. Moreover, the flood area decreased when the resolution was changed from 10 m to 7.5 m. Therefore, further research in the catchment of Mexico City will have to concentrate on using a finer grid size, and a larger range of resolutions to compare the depth and extent of flooding.

5.4 Flood hazard analysis of buildings

Hazard is 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. UNISDR (2004)

Flood hazard maps are important tools for understanding the hazard situation in an area. Hazard maps are important for planning development activities in an area and can be used as supplementary decision making tools. Type of flooding, depth, velocity and extent of water flow, and direction of flooding characterize them. They can be produced based on specified flood frequencies or return

periods. Flood hazard is determined by the conjunction of climatic and non-climatic factors that can potentially cause a flood and is usually estimated in terms of a rainfall event or 'design flood'. The estimation of flood probability or hazard combines statistics, climatology, meteorology, hydrology, hydraulic engineering, and geography. In places where the flow data are not available because there are no gauges, or are of poor quality, other approaches are used. [CNA, 2011]. Moreover, this information is combined with topographic, infrastructure, population and other geographic data in order to compute the flood hazard.

Urban areas are often located in hazard-prone locations such as low-elevation coastal zones, or in valleys at risk from flooding as in the case of Mexico City. (OECD, 2009). Urbanization causes expansion as cities grow outwards in order to accommodate population increases. Urban expansion alters the natural landscape, land uses and land cover by changing water flows and increasing impermeable areas. Moreover, urbanization in river flood plains and other areas of catchments could change the frequency of flooding. The changes in land use caused by urbanization have an effect on soil conditions and the nature of run-off in the area. Increased development of impermeable surfaces leads to an increase in overland flow and reduced infiltration. Furthermore, urban centers reduce rainfall and increase night-time temperatures and urban heat islands caused by lack of vegetation, can modify the hydrology of an area. (OECD, 2009)

Some of this increase in urban expansion can also be associated with inefficient land use and planning policies. However, there is a need for accommodating expanding urban populations. Also, higher densities are not necessarily a solution for reducing urban flood risk, as they often go together with increases in non-permeable surfaces, occupation of vulnerable terrains, and levels of congestion, which can compromise the operation of infrastructure services. Figure 5.24 depicts the impact of flooding on an informal settlement.



Figure 5.24 Informal Settlements affected by flooding. [UN-HABITAT]

Furthermore, the concentration of people in urban areas increases their vulnerability to natural hazards and climate change impacts. Vulnerability to flooding is particularly increased where inappropriate, or inadequately maintained infrastructure, low-quality shelters, and lower resilience of the urban poor interlace.

The fact that rapid urban expansion typically takes place without following structured or agreed land use development plans and regulations makes conditions even more problematic. In addition, as the urban poor are often excluded from the formal economy, they lack access to adequate basic services and because they cannot afford housing through the market they are located in densely populated informal slum areas that may be vulnerable to flooding. [UN-HABITAT].

Houses of poor people in these most vulnerable informal settlements are commonly constructed with materials and techniques that cannot resist extreme weather. In addition, fast urbanization in low-income and middle-income nations normally occurs in such high-risk areas. Therefore, an increasing part of their economies and populations are put at risk. [World Bank, 2008]

In order to analyse the flood hazard of some building types in Mexico City, the flooded area contained in the red circle as shown in figure 5.25 was assessed,

Chapter 5 – The Modeling Approach: Strategy, Data And Application

using data from the institute of geography and statistics (INEGI), which lists the buildings and infrastructure in each neighborhood of Mexico City and their address, according to the economic activity they are involved.

This area could possibly be flooded due to overflow in the Grand Channel or the Remedios Channel.

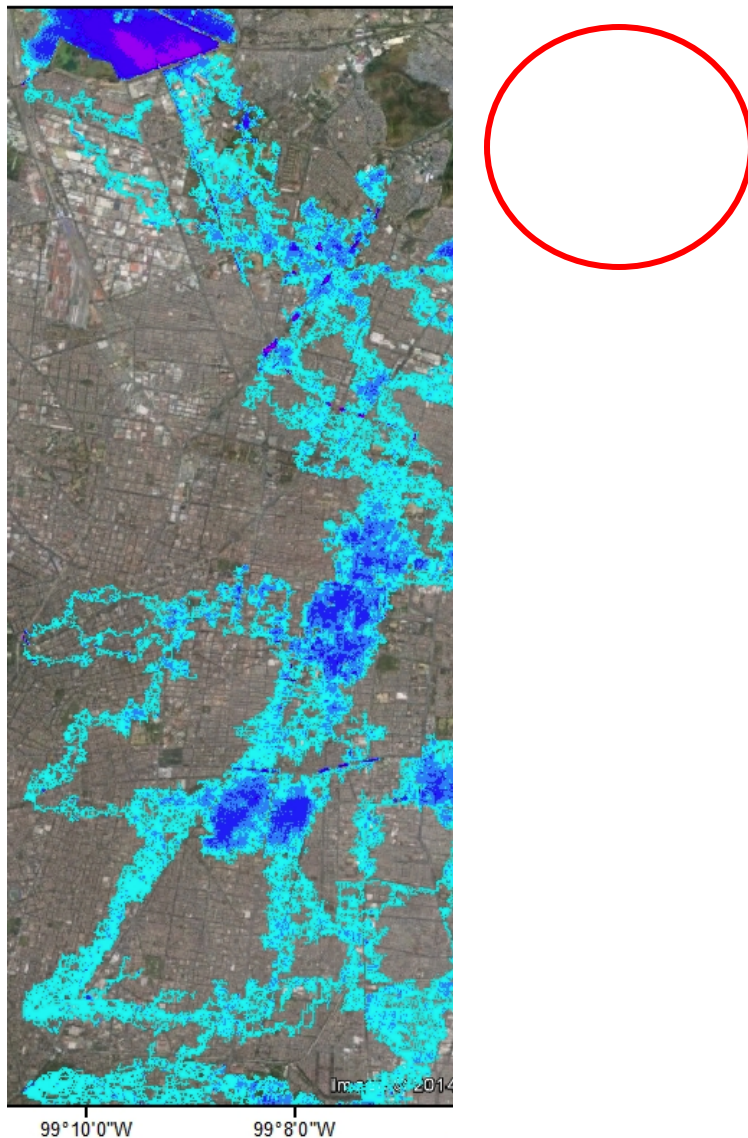


Figure 5.25 In order to analyse the flood hazard of some building types in Mexico City, the flooded area contained in the red circle was assessed.

The flooded area include parts of the following neighborhoods: Altavilla, San Miguel Jalostoc, 25 de Julio, El coyol, Arcos Esmeralda, Atzacolco and González Romero.

Chapter 5 – The Modeling Approach: Strategy, Data And Application

According to the data of buildings and their economic activity, provided by INEGI, the buildings and parks that would be affected by the flood as well as the flood depth experienced by them are shown in table 5.5.

Building type.	Number	Flood depth (m)
Government administrative.	1	0 - 0.5
Hotels	1	0.5 – 1
Churches	3	0 - 0.5
Hospitals	1	0 – 0.5
Parks	2	1 – 2
Stores	5	0 – 0.5 (3) 0.5 – 1 (2)
Factories	1	0.5 - 1

Table 5.5 Buildings types affected by flooding in the neighborhoods of Altavilla, San Miguel Jalostoc, 25 de Julio, El coyol, Arcos Esmeralda, Atzacolco and González Romero, and the flood depth for each building type.

In addition, figure 5.26 depicts the flooded area analysed and the location of the affected buildings and parks.

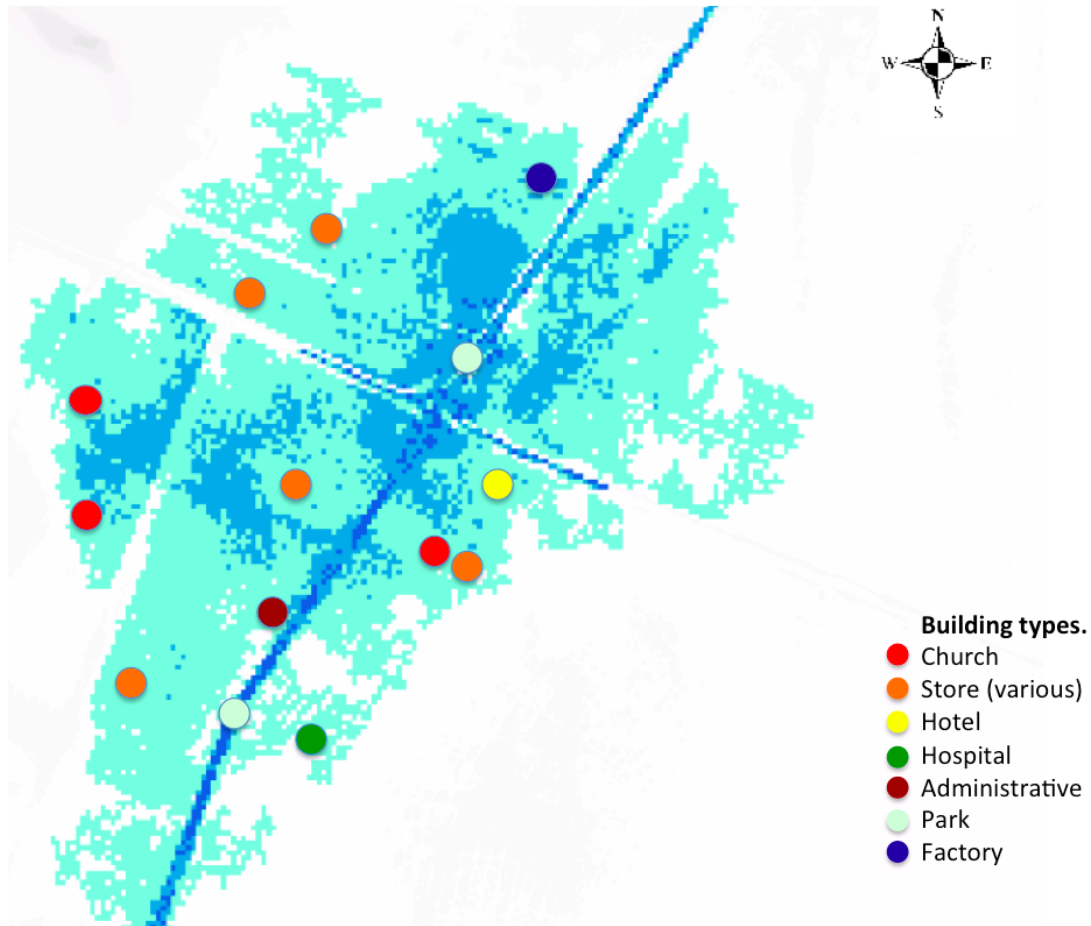


Figure 5.26. Buildings affected by flooding simulated in MIKE 21 with a 20 m grid size.

5.5 Conclusions about modeling approach and results.

As a conclusion, the hydrological modeling approach gave acceptable results based on the simulated discharge and these results proved to serve the purpose of serving as boundary conditions for a flood hazard model in MIKE 21.

The flood maps generated in MIKE 21 are the first ones for the Mexico City catchment that cover the entire area of the basin. Flood maps of smaller sections of the catchment have been developed by the National University (UNAM) and by the center for disaster prevention (CENAPRED), however, these maps are not publicly available. Therefore, a comparison with those maps was not possible.

However, images were found of a conference presentation made by the water commission of Mexico [CONAGUA, 2011] for the flooded area where the Remedios channel enters the reservoir East of the airport. This area is contained in the red circle in figure 5.27.

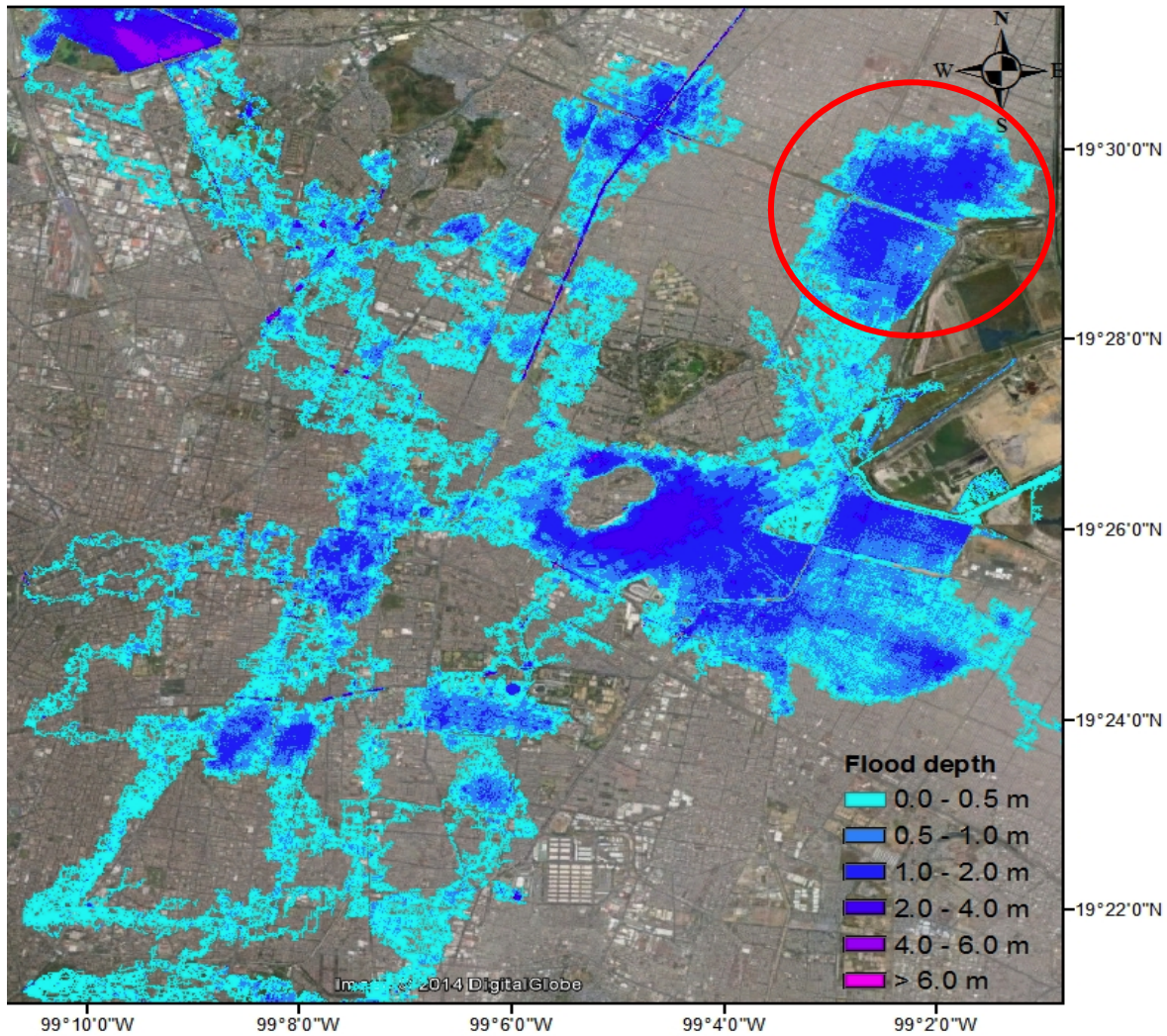


Figure 5.27 Flooded area where the Remedios channel enters the reservoir East of the airport.

The following figures are the only images found of flood modeling for Mexico City. They represent the Southern and Northern flood areas at the point where the Remedios channel enters the reservoir at the East of the airport in Mexico City.

According to CONAGUA, (2011), these simulations were carried out for a hypothetical case of failure in the channel that would cause over-flow in the points indicated by the red points and arrows.



Figure 5.28 Southern flooded area where the Remedios channel enters the reservoir at the East of the airport, with points of hypothetical channel failure. [CONAGUA, 2011]

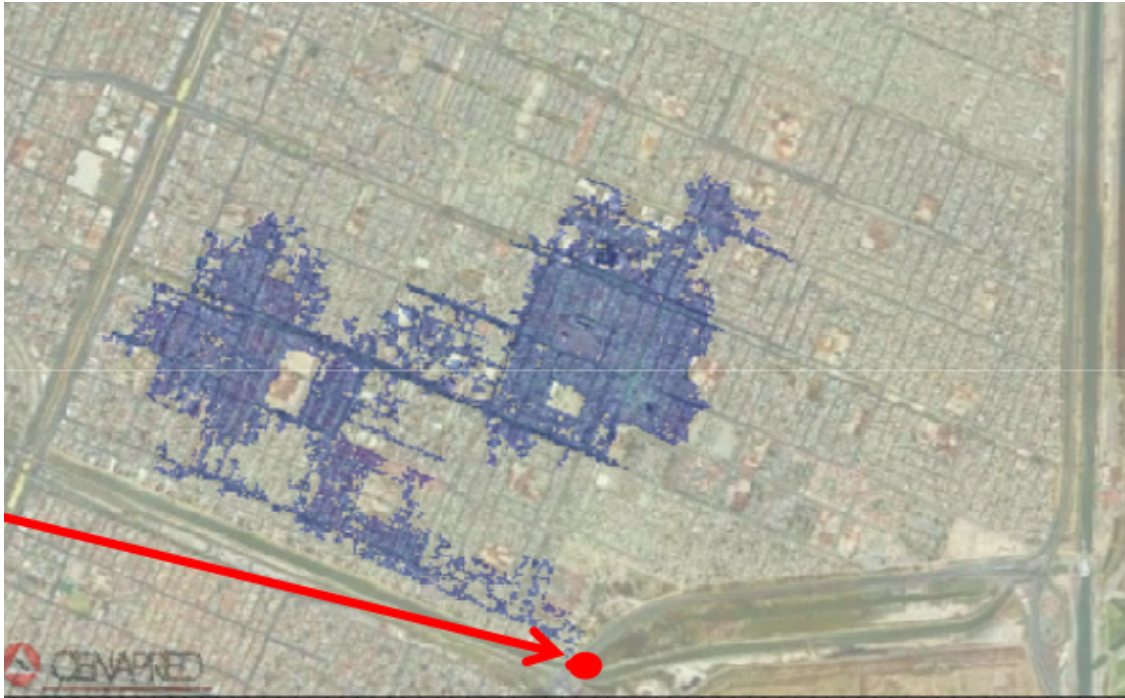


Figure 5.29 Northern flooded area where the Remedios channel enters the reservoir at the East of the airport, with point of hypothetical channel failure. [CONAGUA, 2011]

These images provide a starting point for comparing the results of this study with other flood hazard models as seen in figure 5.30. However, as the data of flood extension and depth produced by CONAGUA is not available to the public in a raster format or vector format, a comparison of area is not yet possible.

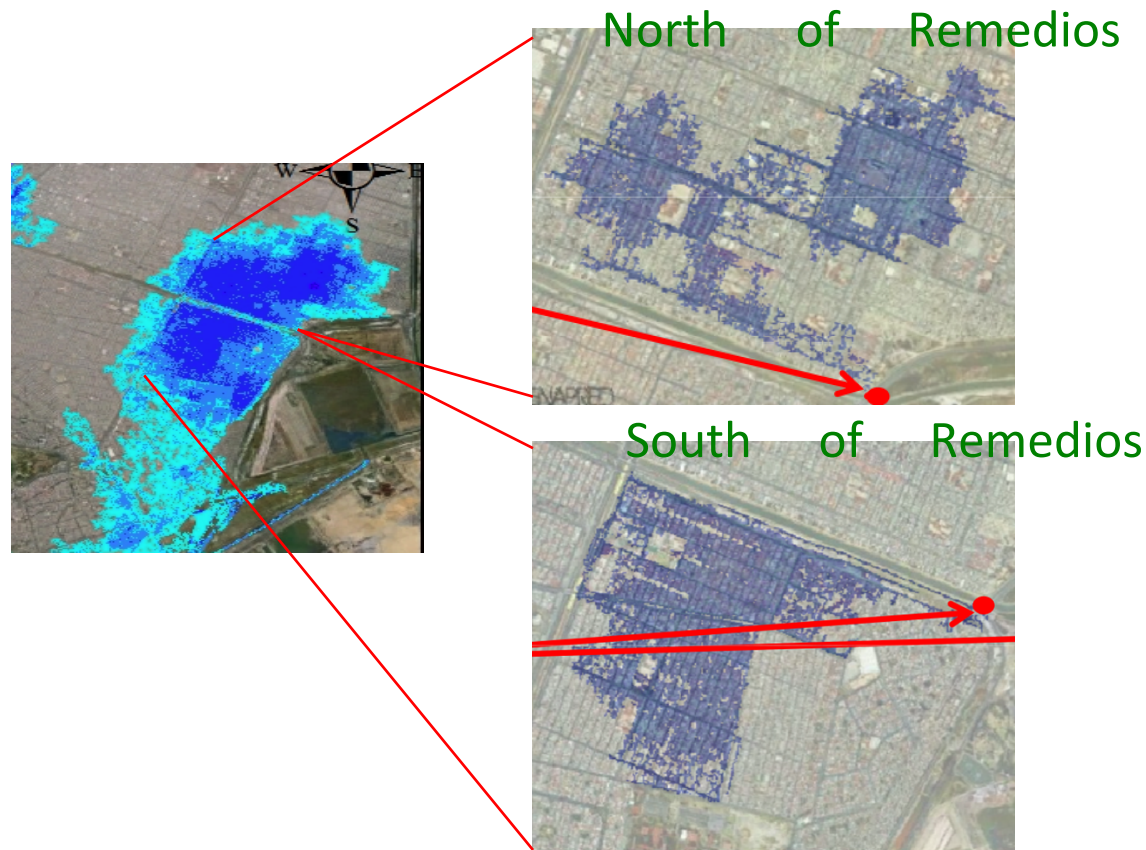


Figure 5.30. Comparison of simulated flood in Remedios channel using MIKE 21 with images of flood extent created by CONAGUA.

However, the present study can be considered as the first hydrological study of the Mexico City catchment that incorporates land use and soil types data, as well as the rainfall- runoff process of the entire catchment.

In addition, due to its modular set-up, future work will be able to integrate more data that becomes available in the future, such as new gauged data of discharge and rainfall, groundwater data and new land use data taking into account the increase in urbanization.

This work helps the local authority in its ability to responding actively with future floodings. However, the flood map only supply the flood depth and flood area. Other information will have to be presented in the next studies, such as duration and velocity. Regarding to the potential flood damages, these will be discussed in the following chapter.

Chapter 5 – The Modeling Approach: Strategy, Data And Application

This flood model will be presented to the council of science and technology (CONACYT) and to the water commission this year. A presentation of the hydrological model last year had a positive response by the flood modellers in the water commission and in the national university. According to these institutions, it is a priority for the near future to carry out further studies of flood hazard in more areas of Mexico City and the country of Mexico, and if the authorities decide to apply this hydrological model to aid in their decision-making, it would be considered an important success.

Chapter 6. ECONOMIC FLOOD DAMAGES

Summary

There is a considerable amount of international publications that provide evidence of extensive knowledge in the field of damage estimation for different types of assets and for human life. However, experts and academics disagree about the methods and models to be applied. The division of damage into direct and indirect, and tangible and intangible is routine, but interpretations of what is considered a direct and indirect impact differ. [Jonkman et.al, 2008]

Additionally, there are various viewpoints regarding damage appraisal, such as financial and economic valuation based on market values or imputed values accounting for the depreciation of assets based on historical values or replacement values, while variation is also found regarding the scale of analysis.

This chapter discusses some of the approaches for flood damage estimation in several countries. In addition, an approximate estimation of damages is carried out for a flooded area of Mexico City corresponding to the flood maps in chapter 5.

6.1 Flood damage.

6.1.1 General

A flood is considered a flow or invasion of excess water by surface runoff or by the accumulation of these on flat lands caused by a lack or insufficiency of both natural and artificial storm drain. The magnitude of a flood caused by hydro-meteorological events is dependent on the intensity of the rain, its distribution in space and time, on the size of the affected watersheds on the characteristics of the soil, and on the natural and artificial drainage of basins. [Bremer and Lara, 2001].

Flood damages are normally quantified to determine which combinations of floods and affected populations result in the greatest damages, or to determine the relative effectiveness of alternative intervention strategies.

Chapter 6 – Economic Flood Damages

What each stakeholder wants to know about flood damages varies between stakeholders and sometimes between decisions. Some of the different choices of the different stakeholders are:

- Those who have an interest in implementing flood risk management measures have to consider the benefits and costs of the measures in their decisions before the event has occurred.
- Provincial ministries should have an estimate of the amount of tax money to be spent on flood protection.
- Emergency planners are interested in defining the high risk areas of flood damage to concentrate their efforts in this areas more than others.
- National governments in countries that were hit by a flood event, usually have interest in knowing the magnitude of the flood, the estimate of damages and the total loss for the nation and the economy was.
- Insurance companies are interested in calculations of economic flood damage, specifically in insured financial loss referring to their clients.
- Private firms and even private house owners might also be interested in the amount of damages that potential floods events might cause to their property. Based on this information they decide to buy a flood insurance policy or invest in private flood protection measures. For this purpose, researchers in several countries have developed equations that relate the height of flood and the corresponding flood damage based on standardized building types. [Messner et al., 2007]

Jonkman et.al (2008) pointed out that an approach was missing which could bring together the modeling of physical damage, environmental damage, public health impacts, and economic damage.

Regarding to the economic damage, the following was written: “a modelling framework that captures the working of an economic system, as well as any disturbances therein is needed”.

In order to have a more standardized approach for damage assessment, governments in several countries have been developing standardized systems for the estimation of damage due to flooding. Some examples are: The HAZUS methodology developed in the USA, and the guidelines for cost-benefit analysis (CBA) developed in the UK.

In 2007, Messner et.al, published guidelines aimed at governmental authorities and implementing bodies dealing with ex-ante flood damage evaluation in countries just starting with flood damage evaluation studies and in experienced countries as well, in order to have a consistent set of assessment principles for flood damage evaluation to improve the quality of these studies.

Historically, it is government agencies that have used economic evaluations to validate their decision-making; however, the new emphasis on governance gives this responsibility to the stakeholders. That changes the participation of experts from determining the optimum intervention strategy to advising the stakeholders on what they want to know but also what they need to know.

6.1.2 Types of flood damage.

Although the terminology differs occasionally, flood damages are mostly categorised firstly in direct and indirect damages and secondly in tangible and intangible damages (Smith & Ward 1998; Parker et al. 1987; Penning-Rowsell et al. 2003; Messner & Meyer 2005).

Direct/indirect damages: Direct flood damage is related to the physical contact of flood water to humans, property and the environment. This includes damage to buildings, economic assets, loss of standing crops and livestock in agriculture, loss of human life, immediate health impacts, and loss of ecological goods.

Indirect flood damages are caused by disruption of physical and economic linkages of the economy, and the extra costs of emergency work to prevent flood damage. Some examples are: reduced economic activity and individual financial hardship, as well as adverse impacts on the social well being of a community. Indirect damages include disruptive impacts, such as loss of trading time and market demand for products. [Department of Natural Resources and Mines, State of Queensland, 2002]

Tangible/intangible damages: Damages that can be represented in monetary terms, such as damages on assets, loss of production etc. are called tangible damages. Casualties, health effects or damages to goods and services which are not traded in a market cannot be assessed simply in monetary terms. Table 6.1 combines the two differentiation criteria and gives some examples for each category. [Messner et.al, 2007]

Chapter 6 – Economic Flood Damages

	Tangible	Intangible
Direct	<ul style="list-style-type: none">• Damage to buildings<ul style="list-style-type: none">• Contents.• Infrastructure.	<ul style="list-style-type: none">• Loss of life• Health effects• Loss of ecological goods.
Indirect	<ul style="list-style-type: none">• Loss of production• Traffic disruption• Emergency costs	<ul style="list-style-type: none">• Post-flood recovery• Vulnerability of survivors.

Table 6.1. Types of flood damages and examples. [Penning-Rowsell et al. 2003; Smith & Ward 1998]

Furthermore, Smith & Ward (1998) distinguish among primary damages, which result from the event itself, and secondary damages, which are somewhat removed from the flood. For example, the loss of production of a firm, which is flooded, would be classified as primary indirect loss. The induced losses of production of customers or suppliers due to backward and forward links would be designated as secondary indirect damages. [Messner et al., 2007]

In regard to indirect damages, figure 6.1 represents the functioning of an economic system over time as a trajectory. When the economic system is affected by a perturbation, it declines and slowly recovers.

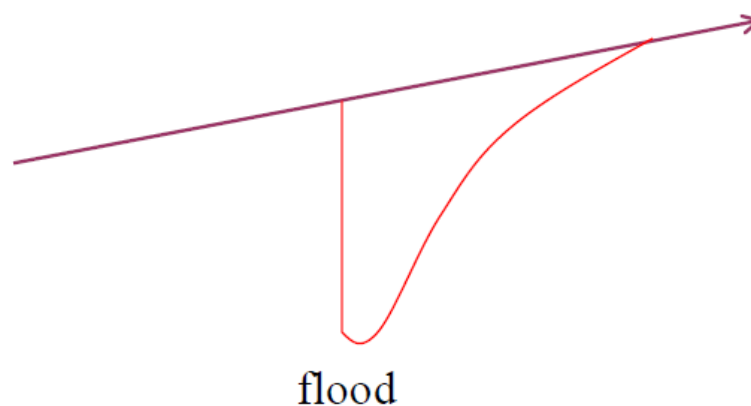


Figure 6.1. Perturbation of an economic system hit by a flood. [Messner et.al, 2007]

Chapter 6 – Economic Flood Damages

The magnitude of indirect damage has been determined in past studies by three factors (Cochrane, 2004)

- Where the economic boundary is defined
- The degree of economic integration
- Pre-disaster economic conditions

6.1.2 Actual and potential damages:

The consideration of potential versus actual damages presents an additional difficulty. Commonly, an assumption is made that nothing will be done to subtract susceptible assets from the area vulnerable to flood. However, displacing possessions to flood-free areas can attain decreases in potential damages. Factors such as the warning time, access to flood free refuges and the flood readiness of the community at risk must be taken into account (see Figure 6.2)

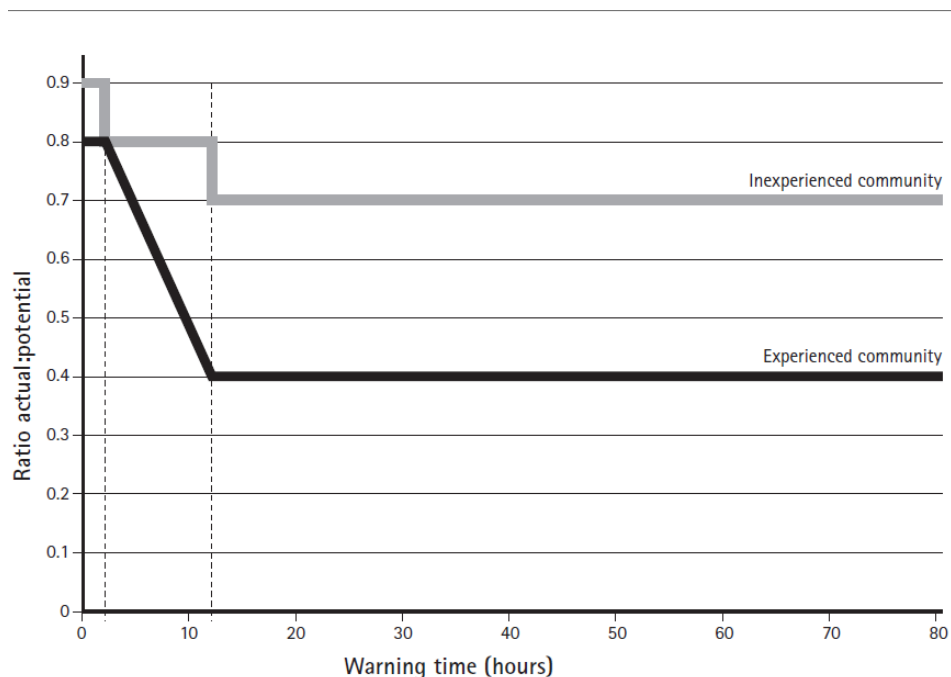


Figure 6.2 The relationship between actual and potential damages. [Reproduced from Read Sturgess and Associates, 2000]

6.1.3 Methods for estimation of direct economic flood damages

The methods for estimation of economic flood damage are generally focused on direct damages that can be assessed through three types of procedures: Vulnerability analysis, conceptual methods and direct evaluation.

The direct evaluation methods have been the most developed of the three, and different methodologies exist in several countries. Some significant studies include the work of Penning-Rowsell and Chatterton in England (1977), Jonkman et al (2008) in the Netherlands, Boyle et al (1998) in Canada, Dutta et al (2003) in Japan, Nascimento et al (2007) in Brazil, and Baró et al (2007) in México.

These studies focus on the detailed evaluation of impacts considering the inventory of damage in affected areas after the event, or modeling a flood event constructed to predict potential damages. These procedures relate the damage to variables such as water depth, flow velocity and flood duration. A method commonly used to estimate direct damage is the application of depth/damage functions. This method requires a spatial database for the specific area of study, which includes information on land use, hydrology and human activities, and the objective is to obtain water depth/damage curves and functions. [Baró et.al, 2007]

The damage to residential and commercial property by floodwaters depends on the value of the building structure, the value of its contents, and the vulnerability of each to damage.

Property inundation levels are calculated using information on ground heights, flood heights and property floor levels. Ground heights may be estimated from topographic maps, sewerage plans and building approvals. Flood heights are predicted using numerical flood modeling or flood extent maps of previous flood events. Floor levels are estimated from building approval records or by traditional survey techniques.

Indirect damages such as clean-up costs for residential and commercial properties are commonly measured as a proportion of direct damages due to the difficulty of calculating them. [Department of Natural Resources and Mines, State of Queensland, 2002]

According to Messner et al. (2007) three basic steps must be followed in every flood damage evaluation study.

Step 1:

Find an adequate approach for a certain damage evaluation study. The choice depends on the scale, the study objective, the availability of resources, and the availability of pre-existing data.

Therefore, the size of the area under investigation is important. Due to the fact that very precise methods require more time and resources than less detailed methods, and that the resources are usually limited, the most precise methods are often restricted to small areas under investigation, while studies with a research area of regional size have to rely on less detailed methods.

Furthermore, the method to be chosen and the precision of the results of a specific study must match with the objective of the study. If the goal of the study is to know an approximate of the amount of damages, a less precise method might be sufficient. On the other hand, if single flood protection measures have to be assessed, then a more precise method will be necessary.

This will determine the resources needed. Although it would be desirable for every study to come to results with the highest level of precision, this is often not possible due to budget or time restrictions.

Indeed, the effort or costs to carry out a certain method of damage evaluation can be reduced if the required data already exists. If, for example, land-use data already exists, this may facilitate the application of detailed approaches on a regional or even national scale.

Step 2.

Determine which damage categories should be taken into account. In general , the parameters which have the greatest impact upon the total damage should be identified. Usually, direct, tangible damage contributes a significant proportion of the total damage. Nevertheless, indirect and intangible damage categories should both be taken into account. Direct tangible damage can further be divided into categories such as buildings, inventories, infrastructure, cars, etc; and it can be reasonable to include only the most important damage categories to reduce the effort of the study.

The third step is the estimation and calculation of the values of potentially damaged tangible assets and the gathering of sound information for this task.

Chapter 6 – Economic Flood Damages

The area and depth of inundation are the most important information to be obtained; but also the duration, time of occurrence and velocity could have a significant influence on damage.

Moreover, in order to measure damage in monetary terms, information on the value of assets at risk needs to be quantified. This information can be integrated in two different ways: First, the total value of all assets at risk in a study area is estimated, the damaged share of this total value is then calculated by relative damage functions; or second, the value of elements at risk is integrated in absolute damage functions, showing the absolute damage depending on flood height, duration and velocity.

Finally, damage functions are required to provide information on the dependability of elements at risk against inundation characteristics. They show either the damaged share or the absolute monetary amount of damages per property or square metre of a certain group of assets at risk as a function of the magnitude of certain inundation characteristics.

Currently, the more developed studies around the world consider the inundation depth as the main parameter in these damage functions (depth-damage functions). Others, like velocity, duration and time of occurrence are rarely taken into account. Table 6.2 shows a listing of these parameters and their relevance on flood damage. Furthermore, as the susceptibility of assets at risk depends on their type and attributes, properties of similar type are represented by an approximate damage function. The extent of this categorisation varies between the different approaches.

Inundation characteristics	Relevance
Area	Determines which elements at risk will be affected
Depth	Has perhaps the strongest influence on the amount of damage
Duration	Special influence on damages to building fabric
Velocity	Only high velocities will lead to increased damages
Rise rate	Influence on damage reducing effects of warnings and evacuation
Time of occurrence	Especially important for agricultural products

Table 6.2 Parameters affecting flood damage and their individual relevance. [Messner et al. 2007]

Chapter 6 – Economic Flood Damages

Moreover, in damage evaluation, depth of inundation is considered the most important information because of the perception that inundation depth has the strongest influence on damage magnitude; however, it should be noted that studies of empirical damage data showed that the variability of damages can only be explained to an extent by the depth of flooding experienced. According to Merz et al. 2004, as other flood characteristics are normally not recorded it is difficult to quantify their influence. For example, the duration of flooding is important when calculating production losses but could also influence direct damages. Penning-Rowsell et al. (2003) found higher damages from longer duration of flooding in elements such as mortar, drains, timbers, plasterwork and tiles. They distinguish between short (< 12 hours) and long duration of flooding (> 12 hours) in the damage functions. (Figure 6.3)

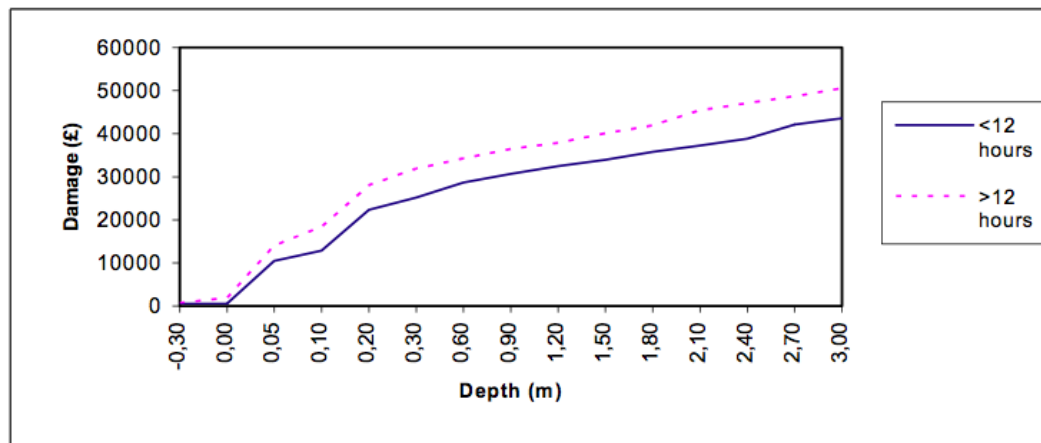


Figure 6.3 Example from the UK for Depth-Damage-Duration Data for Residential Properties [Penning-Rowsell et al. 2003]

Furthermore, the time of the year is important when calculating damages to agriculture. For instance, damages would be high if flooding occurs just before the harvest, but will be relatively low in wintertime.

6.2 Land use data

Land use data is required to know the number, location and type of elements at risk. This information can be obtained by field survey (primary data) or from pre-existing data sources (secondary data). The spatial resolution of land use data may vary considerably:

sometimes single properties are considered (object-oriented data) and sometimes objects are concentrated to areas of relatively homogeneous land use (aggregated data). To receive detailed results of damage evaluation, land use information is necessary, especially on buildings. For a damage evaluation with high precision, object-oriented land use information on buildings is recommended. For micro-scale studies, the information is derived from field surveys. For an application of object-oriented data on the meso or macro levels, secondary sources have to be used. If such a database is not available, aggregated land use data sources are sufficient. [Messner et al. 2007]

After defining the hazard by flood characteristics it is necessary to define the elements at risk as well as their value and their susceptibility against flooding. From the perspective of damage evaluation the ideal land use dataset provides the minimum of variance within a category and the maximum of variance between categories. The advantage of survey data is that all required land use information can be collected at that level of detail as it is needed for damage evaluation. The disadvantage is that field surveys are time-consuming and costly.

However, secondary data can be costly too, especially if very detailed information is needed. But in general it will require significantly less effort and costs to apply existing data in damage evaluation.

The level of detail of land use data is determined by its spatial resolution and the degree of differentiation between different land use types. Detailed data contains information about the location and type of every building. Damage evaluation methods based on this data can be called property-by-property approach. [Penning-Rowsell et al. 2003]

In other data sources properties or buildings are aggregated to areas of more or less homogeneous land use. In the following this type of data will be called aggregated land use data. The spatial information is nowadays mostly stored and presented in digital maps, either in the form of address points, discrete areas or lines (vector data) or in grid format.

The other criteria, the level of differentiation of land use types correlates more or less strongly with the spatial resolution: Data with a high spatial resolution often also has a high differentiation of land use categories.

However, it is important that the categorisation of land use matches with the categorisation used for the quantification of values and for the damage functions. It would not make any

sense to differentiate buildings in more than a hundred types when later only one approximate value and one approximate damage function are used. [Messner et al. 2007]

Object-oriented land use data is often available from secondary sources and varies between countries. Two different kinds of data are address-point data, where each property is represented by a point in a map, and cadastral maps, which also give information on ground floor area of properties in buildings.

It should be mentioned that address-point data, but sometimes also cadastral maps, focus on information on buildings. For the assessment of other areas, like agricultural or traffic areas it might be necessary to use additional use data. [Messner et al. 2007]

6.2.1 Aggregated land use data

In contrast to object-oriented data, other secondary land use data sources aggregate several properties to areas of more or less homogeneous use. However, the spatial extent of these areas is rarely the same as that of the inundated area, therefore, intersections between land use data and inundation area have to be made in order to estimate which part of the aggregated land use units is affected. Therefore, the application of aggregated land use data can lead to some inaccuracies.

6.2.2 Other data

In some studies geomarketing data is used to integrate additional socio-economic information. Geomarketing data is not an official data source but mostly stems from commercial providers. It provides information on a small spatial scale, e.g. for postcode districts, election districts, street sections or single address-points. While the main purpose of this data is to facilitate commercial marketing, it can also be valuable for damage evaluation as additional to land use data described above.

In the Netherlands, for example, such data is used in the standard damage evaluation approach (Kok et al. 2004). In this way information on the number of inhabitants, number and type of flats as well as number and branch of employees per geographical unit is added to get more precise information on these elements at risk than is provided by official land use data.

Table 6.3 gives a short overview of the types and examples of land use data described in this chapter.

Source	Types & examples	Spatial resolution
Primary	Field surveys Cadastral maps Detailed aggregated data	Object oriented: Single properties Address points, Ground floor areas
Secondary	Low detailed aggregated data E.g. CORINE Land Cover	Aggregated: Blocks of similar use Postcode areas, election districts, etc.

Table 6.3 Overview of different land use data types [Meyer, 2005]

In many damage evaluation studies not only one source of land use data is used. The reason for this can be, for example, that one data source does not cover all types of land use.

6.3 Determination of the value of assets at risk

After documenting the location, number and type of elements at risk it is necessary to quantify their value in order to calculate damages in monetary terms. This information can be integrated in the process of damage evaluation in two different ways:

- The total value of elements at risk in the study area is evaluated.
- The value of elements at risk is integrated in absolute damage functions for each category, showing the absolute damage depending on magnitude of inundation characteristics. [Messner et al., 2007]

Which of both approaches is chosen depends on the type of available data. For example, if detailed data on the value of assets is at hand the percentage of property approach may be convenient. If on the other hand a complete set of absolute damage functions already exists the absolute damage estimation approach could be more appropriate. [Messner et al., 2007]

Chapter 6 – Economic Flood Damages

The formula for the calculation of the total damage for a flood event depends on the type of approach chosen and the type of data used. In a general this can be described by:

$$Damage_{total} = \sum_{i=1}^n \sum_{j=1}^m (value_{i,j} \times susceptibility_{i,j})$$

(Eq. 14)

with:

susceptibility $i, j = f$ (characteristics entity i, j , inundation characteristics k , socioeconomic characteristics l)

i = category of tangible elements at risk (n categories possible)

j = entity in an elements-at-risk category (m entities possible)

k = flood type/specific flood scenario

l = type of socio-economic system

susceptibility: measured in percent

Such a calculation leads to a single direct, tangible damage amount in monetary units for each flooding scenario considered. This damage value can be used for the calculation of flood risk (the annual average damage) and for the calculation of net benefits or cost-benefit ratios in the context of flood protection measures.

However, since flooding events and their damages are usually highly spatially diverse, it is advisable not to present the results in terms of one monetary number, but also to prepare maps to show the spatial distribution of damages. This is possible by means of geographical information systems (GIS). Finally, it must be emphasised that all methods for flood damage analysis include uncertainties in their results. These arise, among others, from inaccuracies and generalisation in the data used. [Messner et al., 2007]

6.4 Calculation of economic damage.

As described above, methods of damage evaluation vary considerably regarding the type of data used. Nonetheless, the general procedure followed in nearly all approaches can be described as follows:

To begin with, all the information on inundation characteristics, land use, asset values and susceptibilities have to be related to each other. In other words, inundation data and land use data have to be combined, (intersected by means of GIS) to find which land use units would be affected and what area of them.

Furthermore the asset values and damage functions have to be assigned to the different land use units. As mentioned earlier, two basic approaches can be considered:

1. The absolute or direct damage estimation approach, where information on the value of assets and on their susceptibility against certain inundation depths is used to develop absolute damage functions; and data on inundation depth and land use information are used in these absolute damage functions to make a direct estimation of the absolute damage amount for each property
2. The percentage of property value approach where land use information and asset values are brought together to calculate the total value of assets at risk. This maximum damage potential is then overlaid with data on the specific flooding scenario, and the resulting damage for each is calculated by means of relative damage functions, showing the damaged share of the total value as a function of inundation depth.

6.4.1 Stage–damage curves

They define the association between levels of inundation and damage suffered. For their production surveyed damage estimates for a range of flood levels are obtained. Where locally specific data does not exist, it is recommended to use available stage–damage curves produced as a result of previous flood damage studies. Furthermore, ‘synthetic data’ can be estimated not for actual properties but for standardized, typical property. For this, standard buildings types are defined by their typical size, construction and inventory components; then, the value of these components is evaluated and the vulnerability of each of these items is estimated by expert inspectors or from existing databases. Finally, a damage function for each building type can be derived.

Synthetic stage-damage curves were first proposed by White (1964) and the ability in obtaining them is in deciding on the number of building types to be considered. [Smith, 1994]

In a more recent study, Dutta et al. (2003) presented an integrated model for flood loss estimation in a river basin in Japan. The model combines a physically based distributed hydrologic model with a distributed flood loss estimation model. The hydrologic model considers key processes of the water cycle through physically based governing equations, which are solved to simulate the propagation of water in each of these processes. Furthermore, the model is formulated based on stage-damage relationships between

Chapter 6 – Economic Flood Damages

different flood inundation parameters and land use features. It computes the economic loss to different land use features based on the simulated flood parameters obtained from the hydrologic model for any flood event

In 2008, Jonkman et.al presented an integrated flood damage model currently operated and maintained by the Dutch Directorate General of Public Works and Water Management. This model was developed to integrate the calculation of both direct damages and indirect damages such as the interruption of production outside the flood area and loss of life. Moreover, the model combined information on land use and economic data, and data on flood characteristics and stage-damage functions, supported by GIS, to obtain a damage estimate for several damage categories.

The integrated flood damage model discussed by Jonkman et.al (2008) is based on a database of geographical information, which covers the identified area affected, by a hazard and the asset categories in each unit of this area. The model combines different modules consistently inside one geographical area through a mutual geographical attribute.

To estimate direct physical damage through this method, the flood characteristics are determined, information is assembled on land use data and maximum damage amounts, and functions of stage-damage are applied. The hydrodynamic model produces information about the development of the flood flow, and insight in flood characteristics, such as water depth, flow velocity and the rate at which the water rises. These characteristics can be represented on a map. Because an area can get flooded in more than one way, several flood scenarios are modeled.

In this work, five main categories of assets at risk were distinguished: General land use (for example urban area), infrastructure, households, companies and public utilities and facilities (for example pumping stations). Several sources of data were used to determine the amount of maximum damage for different asset categories and for each of these categories, a specific stage-damage function was estimated and used in the direct physical damage assessment by correlating historical damage data with flood depth.

To evaluate the total direct damage, information on flood characteristics and land use was combined with the stage-damage functions.

In a different study, Baró et.al (2007a) proposed a method for standardized quantification of tangible damages caused by flooding in residential areas and agricultural land, which is based on a catchment located on the upper reaches of the Lerma River in Mexico.

Chapter 6 – Economic Flood Damages

The authors created a database in order to analyze the flood damages, including information on land use and human activities, which in the case of residential areas, consist of the following data:

- Socio-economic characteristics of the population, obtained from the 2000 Census (COESPO, 2001) and INEGI (2000).
- Unit value of buildings from the Government Gazette of the State of Mexico (1998, 2002)
- Information on existing assets in the houses from the Population and Housing Census 2000 (INEGI, 2000) and from field surveys.
- Information of water elevation from a hydraulic-hydrological simulation model.

After defining the assets in each housing type, a percentage of damage was determined for these assets depending on the water level reached inside the house. In the case of damage to structures, a consultation with builders and insurers was held.

With these numbers a graph was constructed (figure), where the horizontal axis corresponds to values of water height, and the vertical axis to the economic damages in Minimum Wage units.

Based on this information a regressive mathematical model was constructed. The model chosen was the one which had the highest value of the coefficient of determination (R^2), and with this equation it is possible to calculate potential direct damages. [Baró et.al, 2007a]

After developing the curves, the authors selected the flood recurrence intervals from previous studies of the area, as well as the estimated flows in the streams of study. Using these flows, the maximum water level was determined, using the HEC-RAS model. Only the predominant type of housing affected was considered for this study and the number of houses affected was determined using the affected surface. For this, a uniform area and distribution of this housing type was considered. Using the stage-damage curve for this type of housing, the damage was estimated for one unit and for each water depth of the different recurrence intervals, and then multiplied by the number of houses to find the total. [Baró et.al, 2007b]

6.5 Estimation of flood damage for a flooded area of Mexico City.

In the present study, a hydrological model in MIKE SHE coupled with MIKE 11 served to make boundaries of discharge for a flood model case of Mexico City. This modeling tool allowed for the creation of maps of flood area and depth. These maps were used to estimate flood damages. In the last chapter, the types of buildings affected by flood in an area of Mexico City were identified and quantified, as well as the flood depth corresponding to each building affected.

This section will present the results of an economic flood damage assessment. These estimations will be for direct economic damages to buildings only. Factors affecting the vulnerability including preparedness of the population were not taken into account as no data exists regarding that.

A rough or approximate calculation of damages was done due to the lack of economic values for building types and the assets inside, which are necessary to create flood damage curves, which in turn allow the production of standardized damage functions.

6.5.1 Damage to housing.

In the case of the Mexico City catchment, the damage equation for economic housing units produced by Baró et.al, (2007b) was applied to estimate damages in this flooded area. This equation is the following:

$$DDH = 1016.6Ln(h) + 2030.7 \quad \text{Eq. 15}$$

Where:

DDH=Direct damage to housing

Ln=Minimum wage.

h= Depth of flood.

Baró et.al, (2007b) created this equation through a method in which the percentage of damage was specified for each flooding depth to the house and to the following assets:

- T.V.
- Refrigerator
- Stove

Chapter 6 – Economic Flood Damages

- Living room furniture
- Beds
- Clothing

Then, the authors calculated the cost of damage per depth interval from 0 to 2.5 meters as seen in figure 6.4 The graph represents flood damage in mexican pesos, against height of flood in meters.

In addition, 5 types of houses where defined by the authors:

- Precarious
- Economic
- Public housing
- Regular
- Good

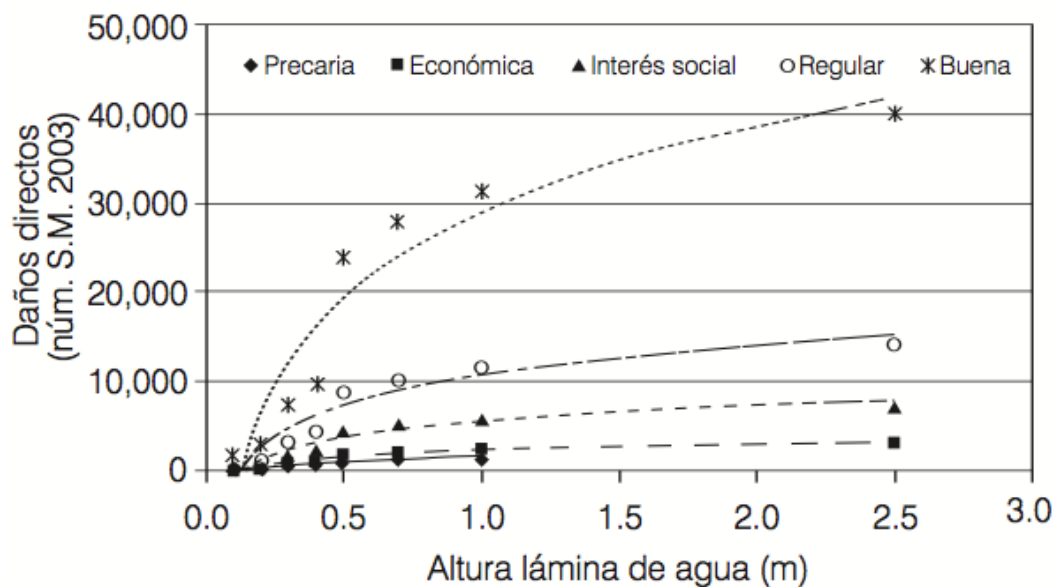


Figure 6.4. Potential damage for 5 types of housing in Mexico and for 5 intervals of flood depth. [Baró et.al, 2007b]

With this information, a mathematical model was created and equation 15 was produced. This graph uses minimum wage as a unit for damage, as the total damage to the house was divided by the minimum wage.

According to INEGI (2016) the neighborhoods considered in the present flood damage assessment of the catchment of Mexico City are considered of low income. Therefore, the

Chapter 6 – Economic Flood Damages

housing type 'economic' was chosen for the flood damage estimation, as precarious housing are not found in this area of Mexico City.

It should be noted that an average of the flood depths was used in order to calculate the total damage to housing.

In order to analyse the flood damages of some building types in Mexico City, the flooded area contained in the red circle in figure 6.5 was assessed.

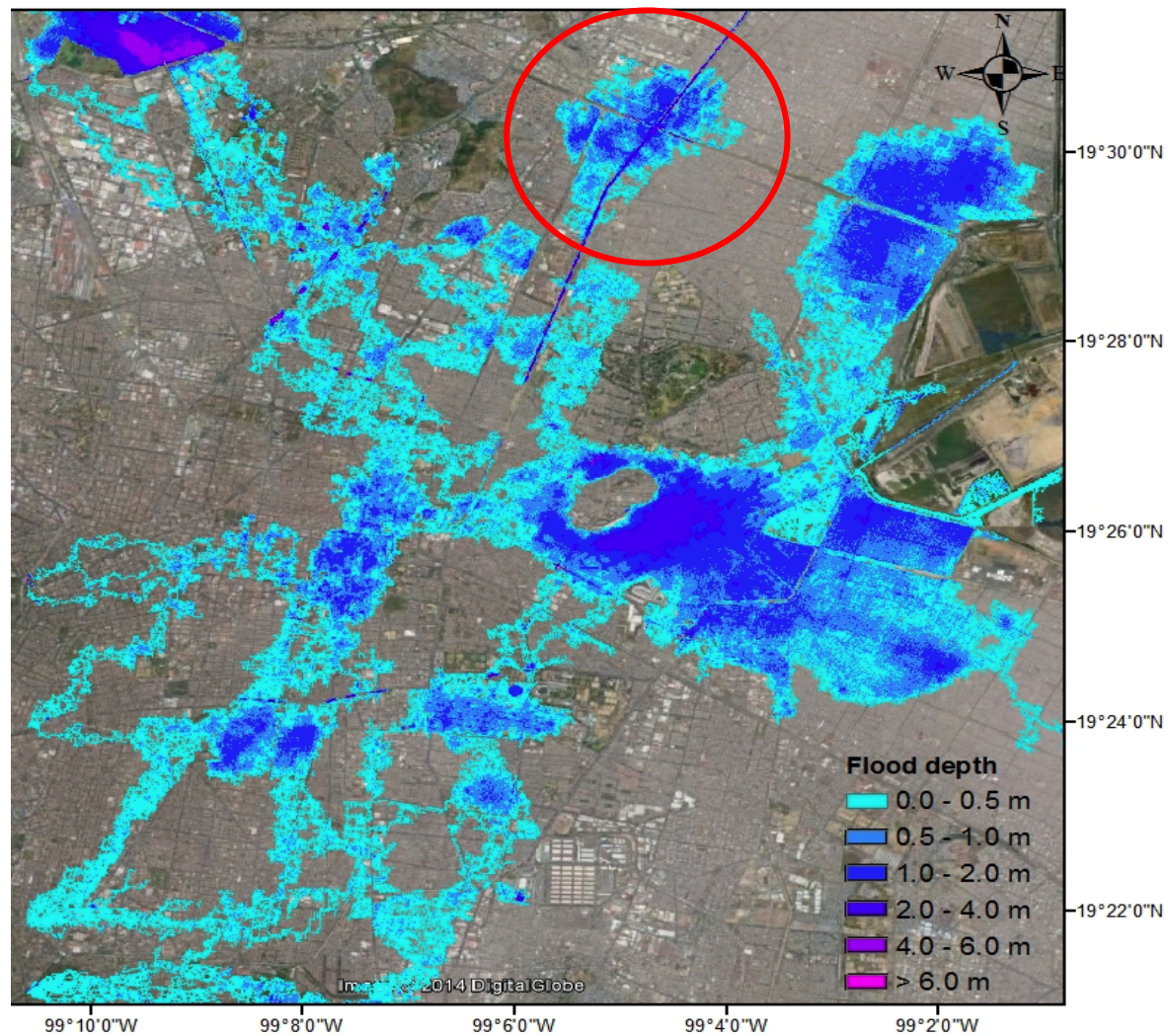


Figure 6.5 The flooded area contained in the red circle was assessed.

Chapter 6 – Economic Flood Damages

In addition, figures 6.6, 6.7 and 6.8 depict the national inventory of housing website designed for public consultaion, as well as examples of housing units per block and of number of inhabitants per block. It should be noted that the consultation system does not allow the downlowad the data, therefore, only a visual inspection was done to estimate an apporximate of housing units and inhabitants affected.

According to this inspection of the national inventory of housing, constructed by the geography and statistics institue (INEGI), approximately 5,100 residences are contained in this area of flooding, and 25,000 residents inhabit his area.



Figure 6.6 National inventory of housing in Mexico created by INEGI. [INEGI, 2016]

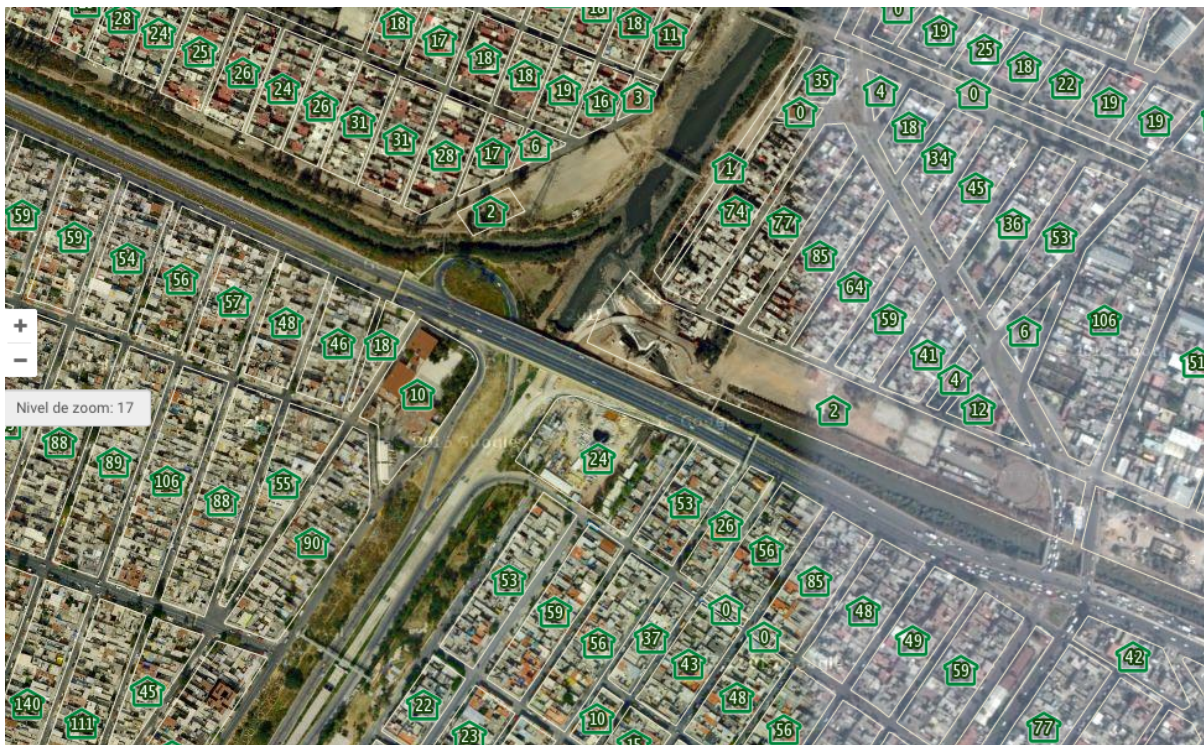


Figure 6.7 Example of the number of housing units in the flooded area of study. [INEGI, 2016]

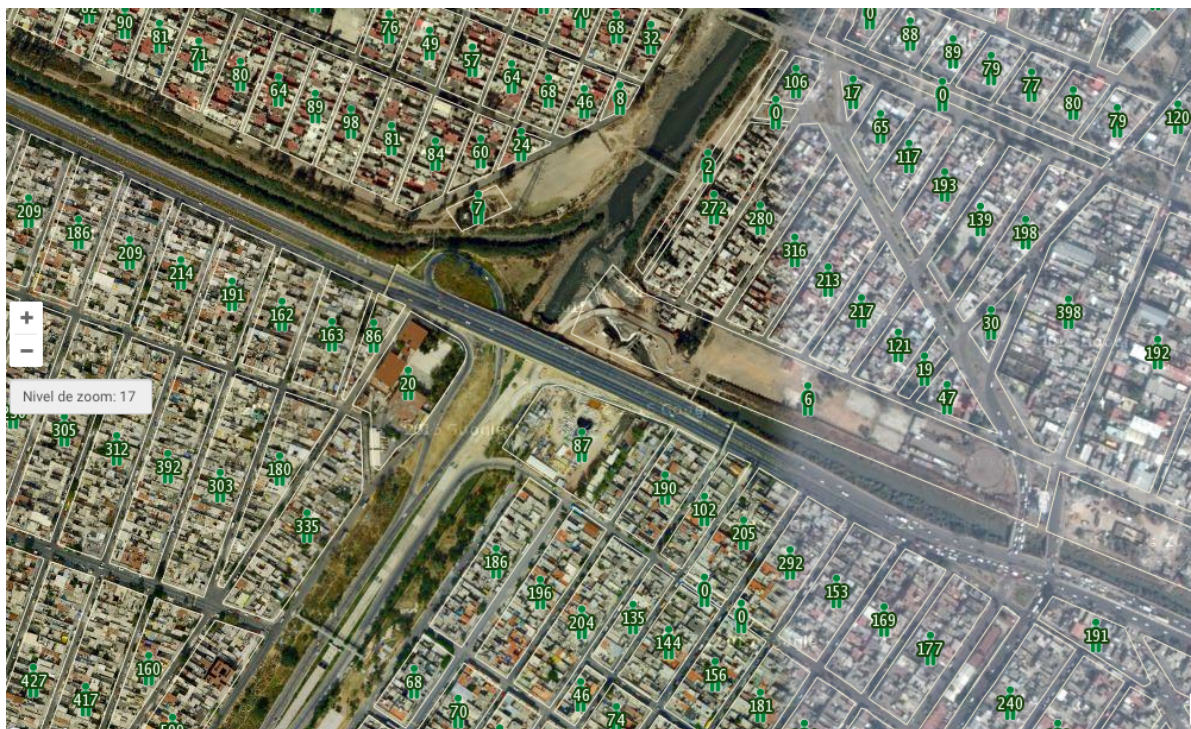


Figure 6.8. Example of number of inhabitants in flooded area of study. [INEGI, 2016]

Chapter 6 – Economic Flood Damages

The flood depth modeled in MIKE 21 varies from 0.5m and 5 meter. Because of the lack of data of houses, only a visual inspection could be carried out, and not a precise determination of the number of units affected for each depth interval. Therefore, an average of 2.75 of depth was used to calculate an approximate of damages. In addition, as the equation for flood damage was designed to use with a varying value of minimum wage, the present value of 73.04 Mexican pesos was used.

Therefore the equation for direct damage to housing would result as following:

$$DDH = (1016.6(73.04)(2.75) + 2030.7) = 206,224.97 \text{ (eq. 16)}$$

This value corresponds to one unit; therefore, it was multiplied by the number of houses to obtain the total damage to housing:

Total damage to housing: $(206,224.97)(5,100) = \mathbf{1,051,747,377 \text{ mexican pesos.}}$

This is equivalent to **56,873,401 dollars** and **51,044,583 euros**.

6.5.2 Damage to buildings.

An important ammount of time and effort was put into the research of building types and their values. This research included contacting the cadastral authorities in Mexico City, the UNAM, re-insurance companies including Munich Reinsurance, and the company Natural Risks Evaluations (ERN).

All of them stated that economic values of buildings in Mexico are confidential information kept by insurance companies, and past studies by the CENAPRED about flood damage did not separate from flood damage, wind damage, fire or other types of damages It was the opinion of these experts that currently only a rough estimate can be carried out for industrial, commercial and office buildings using values of contruction per m^2 .

The table bellow lists the building types, the flood depths, their quanities in the affected area and their values per m^2 .

Chapter 6 – Economic Flood Damages

Building type.	Quantity	Flood depth (m)	Value in MX pesos per m^2 .
Government administrative.	1	0 - 0.5	6,500
Hotels	1	0.5 – 1	11,670
Churches	3	0 - 0.5	3,200
Hospitals	1	0 – 0.5	11,670
Stores	5	0 – 0.5 (3) 0.5 – 1 (2)	3,200
Factories	1	0.5 - 1	6,500

Table 6.4 Building types, quantities, flood depth and value per square meter. [Neodata, 2016]

These values are standard values for Mexico in MX pesos. This research found that some building types are not listed in documents publicly available, therefore some generalizations were made. For example, the value of churches and factories were not available so they were considered same as those of stores. Similarly, the value of hospitals was taken the same as hotels.

In the following table the total value of each type for a determined area of construction is presented. This area was estimated by visual inspection of the buildings using Google earth tool, and the value multiplied by the value per square meter of construction, and by the number of buildings.

Building type.	Quantity	Total value in MX pesos.
Government administrative.	1	6,700,000
Hotels	1	6,698,000
Churches	3	9,216,000
Hospitals	1	44,346,000
Stores	5	52,288,000
Factories	1	449,085,000
		Total: 568,248,000

Table 6.5. Total damage to each building type, for a determined area of construction, and for ground floor only.

Chapter 6 – Economic Flood Damages

Moreover, because no data is available of the vulnerability of each area and each building, the total value of construction will be taken as the total damage for each building type. In the case of buildings with two or more levels, the damage will be considered for the first floor, as it is the one that is affected by flooding.

The total damage in the area is as follows:

Building types	Total damage in MX pesos.
Housing	1,051,747,377
Other types.	568,248,000
	Total: 1,619,995,377

Table 6.6. Total damage to each building type.

The approximate total of direct damage for buildings and houses in the area of study is equal to **78,749,457.79 euros**.

6.6 Conclusions.

As mentioned before, this is a rough estimate, and the uncertainties with this calculation will be discussed in the following chapter.

The methodology proposed for estimating direct economic flood damage, can be applied to other areas of Mexico City and of the country of Mexico. However, as no damage functions exist in Mexico; except for the residential and agricultural cases, only an approximate of damage is the possibility to this day.

Further work will need to make an effort in obtaining values of buildings and the assets they contain. This information could be provided by the insurance companies to the government as confidential data, and then used to create damage functions.

Furthermore, it would be of great help to have the housing land use data available for download as raster or vector format. This data can then be combined with the flood maps created during modeling and the exact number of residences affected identified.

Nevertheless, this results represent the first known assessment of flood damages in Mexico City in which the flood extent and depth is modeled using results from a deterministic, physically based hydrological model; proving the capacity and competence of this type of models.

Chapter 6 – Economic Flood Damages

The following step will consist on comparing this methodology with the method used by the water authorities and by researchers in Mexico, in order to contribute to the enrichment of the hydrological studies in Mexico.

Chapter 7. ANALYSIS OF UNCERTAINTIES.

Summary

The several components and methodologies associated with hydrological modeling carry a certain level of uncertainty to the results obtained in these studies. Therefore, these uncertainties should be listed, so that decision makers have a clear understanding of the validity of the results and can take well-informed decisions taking this into account.

In this chapter, the following sources of uncertainty are discussed:

- Possible quality problems of rainfall data in Mexico specifically.
- Uncertainties in streamflow simulation,
- Rainfall uncertainty,
- Uncertainty in the discharge estimation

7.1 Possible quality problems of the rainfall data in Mexico

One source of uncertainty is the rainfall data. It is expected that for a well-calibrated hydrological model that adequately represents the important runoff processes within the catchment that the major factor contributing to the uncertainty in the predicted flows is the uncertainty in rainfall.

Several authors suggest that this is the most important contribution to model uncertainty. For example, Refsgaard et al. (1983) showed that variations due to uncertainty in rainfall estimations are significantly larger than the uncertainty due to parameter variations. However, this conclusion depends strongly on catchment size and response time, on the model and on the assumptions made in representing the different sources of uncertainty. Rainfall uncertainty may arise from instrument bias or error, inadequate spatial or temporal resolution and in the case of forecasts, the inherent chaotic nature of weather systems. [CNA, 2011]

When entering the digitized data through the meteorological database, certain quality control criteria are applied. For example, the temperatures are checked not to be

unrealistically high or low, the maximum of the day is checked to be higher than the minimum of the day, among other measures. But it is perfectly possible that erroneous data (either because they are incorrect on the paper record or because they were wrongly transcribed by capturing) are present.

The Mexican water comission (CNA) in recent years has undertaken additional efforts to assess the quality of the data. Internally the CNA uses quality ratings for prioritizing which data (from the millions available) should be verified against the original paper record. But the correction of errors found may take several years. [CNA, 2011]

7.1.1 Potential problems in homogeneity

There may be problems that limit the usefulness of the data in the CNA database. This problem is the lack of homogeneity of the time series of some variable in some stations.

There could an abrupt change, which can be difficult to identify by the user. There are proven techniques to identify these in-homogeneities automatically or semi-automatically. The CNA, in recent years has made efforts to identify at least the first apparent abrupt inhomogeneity in each series.

Not all in-homogeneities in the time series are abrupt. For example, the fact that a tree, originally sufficiently small and sufficiently far from the station that it does not affect the exposure of the gauge to rainfall, grows over time and begins to decrease this exposure when the wind is directed from the tree to the station. The gradual scope of the urbanized area on the site of the station can also affect this exposure of the gauge to the rain. This occurs gradually, creating an effect of rising or falling ramp-shaped statistics, and these in-homogeneities are much more difficult to identify. [CNA. 2011]

7.1.2 Possibility of delay problems.

The fact that data does not exist in the database does not necessarily mean that no such measurement exists. The data, although measured, may still be in possession of the operator, can be expected to be digitized or may be waiting to be ingested by the database. The reality is that in a world with diminishing government personnel, data are not collected as frequently as they should, nor are digitized as fast as it could. This possible delay in the appearance of recent data is especially important when a recent

event motivates the relevant authority to take flood control measures. Intuitively, this last event tends to be taken as the "design" of the measure of flood control.

7.2 Uncertainties in streamflow simulations

Moreover, operational flood management and warning requires the delivery of timely and accurate forecasts. The use of distributed and physically based forecasting models can provide improved streamflow forecasts. However, for operational modelling there is a trade-off between the complexity of the model descriptions necessary to represent the catchment processes, the accuracy and representativeness of the input data available for forecasting and the accuracy required to achieve reliable, operational flood management and warning.

Uncertainty in hydrologic modelling may arise from several sources: model structure, parameters, initial conditions, and observational data used to drive and evaluate the model (Liu & Gupta, 2007).

In spite of the effort made to reflect the reality of the hydrological cycle in the catchment, the MIKE SHE model of the present study did not achieved an optimal result due to these inaccuracies. The statistical coefficients such as Nash Sutcliffe, correlation coefficient, and RMSE can be greatly improved. Hence, this model has many potential uncertainties to simulate the hydrological process.

The land use, soil property or roughness coefficients, which are simplified, are important causes of underestimation or overestimation of this model. Another issue influencing significantly the model uncertainty is the rainfall which is a key factor in hydrologic processes. Rainfall spatial variation affects heavily both runoff generation and hydrologic processes in a catchment (Moon et al., 2004). The quality of spatial rainfall distribution usually depends on the characteristic of the study area and the rain gauge density. In this model, the rainfall input is considered as a source of uncertainty.

Moreover, the insufficiency of ground water data is seen as a major source of uncertainty for simulating hydrological process, and in Mexico City no data exists, therefore, this component was not taken into account. Regarding to the method solving process in MIKE SHE, selecting the method for modelling components of the model also adds several sources to uncertainty. For example, there are three functions to select for unsaturated flow such as Richards equation, Gravity flow, 2 layer UZ. The Richards equation is estimated to be the best method for simulating unsaturated flow but for this study,

however, the 2 layer UZ was chosen by the simple and short processing time. So, it can be stated that the algorithm for a model component has a particular impact with the model accuracy.

The coupling between MIKE SHE/MIKE 11 additionally adds potential uncertainties. It could affect notably water exchanging between flood plains and river beds. The number of simulating branches and solved intervals in MIKE 11 is considered as a primary uncertainty source. In this model, the number of cross section is of restricted quantity, even when it is acceptable. In addition, the quality of hydrologic model for reproducing hydrological process is affected by the time factors. The time step in this MIKE SHE model of six hours might not represent thoroughly what occurs in the hydrological cycle of a catchment. Moreover, the time period of the model is only 5 years, which can be not sufficient to bring represent extreme events of a higher return period.

7.3 Uncertainty in the gauged discharge data.

For standard stream gauging methods World Meteorological Organisation (WMO) (1994) estimate the measurement uncertainty of gauged streamflows as 5% standard error at 95% confidence interval. Usually, gauging personnel do several measurements of the amount discharge with a corresponding water depth, and a rating curve is used to estimate flows. In the case of Mexico, the CNA has acknowledged that in several stations, this method was not followed. Instead, an average of discharge was estimated using several measurements with no specific time interval. This will cause a poor resolution over some intervals due to the lack of gauging. The CNA is starting new gauging efforts currently with the aim of creating rating curves, however; this data is not yet published. [Butts, 2004]

7.4 Uncertainties in flood damage assessments

The assessment of flood damages imports uncertainties from the climatic/hydrological/hydraulic domain, adds some of its own uncertainties, and exports the resulting composite uncertainties into the decision domain. [Messner et al. 2007].

Although good progress has been made over the last years to improve the precision of ex-ante flood damage evaluation, the results of even very sophisticated methods are

Chapter 7 - Analysis Of Uncertainties

approximate estimations. Uncertainties in the results may arise from the land use data, the value assessment, and last but maybe most importantly from the damage functions.

These uncertainties are caused for example by generalization and categorisation of land use data, the usage of aggregated data on asset values or faults and inaccuracies in the basic data used or in the methods to evaluate them [USACE 1996]

As mentioned in chapter 2, flood depth is a deciding point for the method of flood protection as the pressure caused by the weight of water being held above the pressure point will put stresses on walls and will also drive floodwater through walls. Moreover, if the flood depth is predicted to be greater than 90 cm, as it was found to be for some building types in this study, a flood proofing is not likely to be reasonable. The consensus between experts is that the maximum depth acceptable for wet-proof is 60 cm. Also, it has been found that flood depths greater than 60 cm have more capacity to result in structural damage to buildings.

Furthermore, flow velocity is an important factor in the magnitude of flood damage, however, this hazard model did not quantify its impact and its influence was therefore not taken into account.

In addition, the materials used for buildings and the condition of the building can also influence the extent of damage caused. Masonry construction; which is the main type of construction used for housing in Mexico City, will be able to withstand the impact of floodwaters up to a point but, being a porous material, it will absorb a large volume of water and take considerable time to dry out.

Building quality also has an impact on the ability of a building to withstand flooding. Flash floods in urban environments represent higher risks with respect to damage to buildings. As mentioned before, high levels of density and congestion characterize large cities like Mexico City. Safety standards are frequently overlooked in this city and as a result, floods cause higher impacts. Floodwaters carry with them the debris of waste and the materials from buildings damaged are also swept along, and in an overcrowded space this may lead to considerable additional damage. Therefore, existing buildings located in flood zones are at a particular risk. Therefore, regulations in Mexico should be designed to restrict or prevent new development, and when possible, new buildings can be designed to withstand the effects of flooding by appropriate use of materials and flood resilient measures.

Damage caused to public buildings such as hospitals, clinics, educational buildings, and significant sites such as churches can lead to further indirect impacts like the disruption to education, and a reduction in the capacity for providing both immediate and longer-term

health care. Moreover, floodwaters can mix with raw sewage and increase the incidence of water-borne diseases and also the uncontrolled release of various chemicals – some of which may interact with each other – poses a considerable risk to public health.

Therefore, the decision makers and the public should know these factors that cause damages, as well as the amount of uncertainty in the flood hazard assessment results. If decision makers know how certain or uncertain the damage evaluation estimates are, they can judge for themselves, if these estimates are sufficient as a decision criterion for their decision. [Merz et al. 2004]

Chapter 8. CONCLUSIONS AND PERSPECTIVES

8.1 Conclusions.

As it has been happening since the time of the Aztecs, floods are a fundamental part of the problems in Mexico City. Experts agree that the flood control works outlined here, which are under construction, should be implemented as soon as possible. Otherwise, they will not be many years before flooding that could affect millions of people are present. In the long term, the urban growth should be well planned in the Valley and restricted were nessesary, not only in relation to flooding problems, but also with all services, like the drinking water and transportation. Here the general conclusions for each section of this study are presented.

8.1.1 Hydrological model.

The objective was to develop a methodology for flood event estimation within Mexico City in the specific constraints of limited data sets. The developed approach was based on deterministic distributed model of the catchment of Mexico City based on the physical characteristics of this, most importantly on the geometry or topography.

A deterministic hydrological model was constructed and 3 cases were studied with the data available from Mexican institutions. Results have been compared with discharges recorded at gauging stations. This was done with the aim of testing the premise that a deterministic hydrological model could be an efficient tool for representing the hydrological processes in a catchment when data and resources are limited.

The software calculated the statistical coefficient values of RMSE and E coefficient in Molino Blanco station for the three models studied. As the St. Teresa station was not assessed in models 2 and 3, its results are not included in the table.

- Case 1 gave results reasonably close to the observed data; however, the discrepancies in the months of June, July, August and September reduce the accuracy of the model. Furthermore, in December, the model did not stabilize.

Chapter 8 - Conclusions And Perspectives

- Case 2 obeyed relatively well the main trends of the observed data. In addition, it stabilized during the last months of simulation, as opposed to model 1. However, the results present a regular difference between the gauged data, especially from July to September.
- Case 3 produced results that follow effectively the main trends of the observed data. The unsaturated zone and land use components provide a benefit when representing the hydrological behavior of the catchment. However, an important difference is observed in July and August, when an excess of simulated discharge takes place. The different variables incorporated that conform the unsaturated zone and land use sections should be analyzed to try to find the causes of this difference.

Nevertheless, case 3 provided the best result when representing the hydrological processes of the Hondo River catchment. However, the issues associated to all cases should be resolved before a recommendation of which type of model to be used can be made.

The importance and interest of the deterministic approach in MIKE SHE has been demonstrated for the Mexico City catchment; as the developed tool allowed us to establish a diagnosis on the runoff processes that generate flooding events in Mexico City. The importance of this study should be highlighted since a hydrological study, which includes data of land use and soil types, has not been previously carried out for Mexico City.

Therefore, the results of this study can be considered as a basis for all future physically models of the catchment.

The distributed model allows generating, for a specific rainfall event associated to a given return period, the hydrograph to consider for protection design and population awareness.

However, even when the results of the MIKE SHE Model regarding discharge in the rivers and water level in the downstream are satisfactory, it should be noted that the simulation period of one year limits the understanding of the behavior of the catchment over a longer period.

Moreover, it should be noted that when facing up to the basin with scarcity of data, modellers have to be knowledgeable enough to find the major factors that have effect on model results. There are model structures such as schematization of processes, river geometry cell sizes (DEM and river network), drainage density, rainfall distribution techniques as well as rain gauges density.

Model parameters are the secondary factors to improve the model performance. After that, sensitivity analysis and uncertainty assessment are highly recommended to execute for getting the better model outputs.

The results of the study also confirm that MIKESHE/MIKE11 can be applied to develop physically based hydrological models in the context of lack of data for water resources management. More especially, this tool can be utilized to significantly improve the model results when bearing the physically distributed parameters and its diversity is also displayed by means of encompassing many different hydrological processes such as overland flow, river flow, unsaturated flow and evapotranspiration and their interactions.

It is proposed that in the physically based hydrological model, the calibration should be omitted. Instead, the availability of data allows the modellers to move to a new paradigm of Installation, Validation and Exploitations runs [Cunge, 2003] for deterministic hydrological model development for the compromise of cost and quality of numerical model performance. The combination of the data-driven model and deterministic model (such as MIKESHE/MIKE11) is suggested for basins with data scarcity, especially to save significant financial resources and enhance the model accuracy [Cunge 2003; Gourbesville 2009].

8.1.2 Flood hazard mapping in 2D modeling.

A deterministic hydrological model was constructed and used with the data available from Mexican institutions. Results have been compared with discharges recorded at gauging stations. This was done with the aim of testing the premise that a deterministic hydrological model could be an efficient tool for representing the hydrological processes in a catchment when data and resources are limited, and that the results of discharge from this model can serve to carry out a flood hazard assessment. The MIKE 21 model allowed for the generation, for a specific rainfall event, of the flood extent and depth. These flood maps should be considered for protection design and population awareness. Moreover, according to the flood maps, it is considered that a grid size of 30m is sufficient for the operational management of the city; to take decisions on structural and non-structural measures, and for land use planning because it shows a well defined flood extent and depth. However, taking into account the increase in computational time, a finer DEM resolution should be used to study the benefits of having more topographical detail.

8.1.3 Grid size sensitivity analysis

As mentioned above, the MIKE 21 model allowed for the generation, for a specific rainfall event associated to a given return period, of the flood extent and depth in the catchment. Furthermore, the analysis of total the flood extent obtained with grid sizes of 50m, 30m and 20m, indicate that the flood area increased when reducing the grid size, as opposed to the findings of the reviewed studies, which found that a smaller grid size produces a smaller flood area.

Therefore, further research in the catchment of Mexico City will have to concentrate on the flood hazard evaluation using a finer grid size to compare the depth and extent of flooding, but also a larger range of grid sizes to observe better the trends in flood extent variation.

In addition, applying a high-resolution topography would provide a more accurate flood map. Moreover, the existing flood maps, such as the national flooding index produced by Agroasemex S.A.; a national insurance company, and the flood maps produced by the National Center for Disaster Prevention (CENAPRED) will have to become available in the future to be compared with the results of this study.

8.1.4 Flood control and mitigation

Several choices of measures for flood control have been described, indicating its main functional features as well as some of their advantages and disadvantages, some of its capabilities and limitations and emphasizing negative effects that can propagate upstream or downstream. In a flood control program, several of these options should be compared to achieve the purpose of managing the flow with the design return period. As the solution has to arise from a rational approach of the problem and a study of the various combinations of options, it should not be the result of receiving a proposal from a company or institution. Finally, it is important to note that the inhabitants of regions affected by frequent flooding, must learn how to live with floods, so that they are less harmful than usual.

8.2 Perspectives

The following step in flood hazard assessment will have to concentrate on the use of a finer grid size.

Chapter 8 - Conclusions And Perspectives

Applying a high-resolution topography would provide a more accurate flood map, compared to real flood conditions.

Furthermore, research efforts will have to concentrate on the damages assessment of flood according to the flood risk maps and land use maps. Further research on the economic value of different assets such as industrial and commercial buildings will be required to develop the stage-damage curves in Mexico for these types of buildings. The studies previously carried out in Mexico to estimate direct flood damages have produced stage-damage curves for residential and agricultural areas.

For residential areas, housing types were selected and percentages of damage specified for the assets and the houses. In the case of agricultural land, maize crop has been the subject of study. However, there is still a need for research on other types of crops and on industrial and commercial assets in order to develop the corresponding stage damage curves and loss functions.

Furthermore, damages for this areas need to be evaluated based on hydrodynamic models using the most accurate and recent data, including elevation, historical rainfall, flow rates, past flooding conditions, and information on values and percentage of damage depending on water depth.

In the case of industrial and commercial areas, the assets in each industry type will be defined, and a percentage of damage will be determined for these assets depending on the water level reached inside. In the case of damage to structures, a consultation with builders and insurers will be carried out.

With these numbers a graph will be constructed to relate water height and economic damage, and the flood recurrence intervals from previous studies of the areas will be selected, as well as the estimated flows in the streams of study. Using these flows, the maximum water level will be determined. For each of the flows studied, the flood area will be determined. In the case when flood recurrence intervals and flows are unknown, historical rainfall data will be input to model the hydrodynamics of the system and find its behavior under several amounts of rainfall.

REFERENCES

- Abbott, M. B., Bathurst, J. C., Cunge, J. A., O'connell, P. E., & Rasmussen, J. (1986). 'An introduction to the European Hydrological System—Système Hydrologique Europeen,"SHE", 2: Structure of a physically-based, distributed modelling system'. *Journal of Hydrology*, Vol. 87.
- Aguilar, F; Agüera, F; Aguilar, M; Carvajal, F; (2005), Effects of Terrain Morphology, Sampling Density, and Interpolation Methods on Grid DEM Accuracy; *Photogrammetric Engineering & Remote Sensing*, Vol. 71.
- Aguilar, F; Mills, J; (2008), Accuracy assessment of LIDAr derived Digital elevation models. *The Photogrammetric Record*, Vol. 23
- Álvarez, L., San Juan, C.; Sánchez, C.; (2006) 'Democracy and exclusion in México City, UACM, INAH, CEIICH-UNAM, México, pp. 424; Electronic version
- Aparicio, F.J. (2001). *Fundamentos de Hidrología de Superficie*, Limusa. México.
- Ashley R., Blanksby J., Maguire T., Leahy T. (2010). 'Frameworks for adapting to flood risk: experiences from the EU"s flood resilient city project', *International Association for Hydro- Environment Engineering and Research (IAHR)*. <http://www.sustainable-environment.brad.ac.uk>
- Barnett, T; Pierce, D; Hidalgo, H; Bonfils, C; Santer, B; Das, D; Bala, G; Wood, A; Nozawa, T; Mirin, A; Cayan, D; Dettinger, M; (2008) 'Human-Induced Changes in the Hydrology of the Western United States', *Science*, Vol. 31.
- Baró-Suárez, J.; Díaz-Delgado, C., Esteller-Alberich, M; Calderón, G; (2007). 'Flood damage curves in residential and agricultural areas of Mexico. Part I: Methodology', *Ingeniería hidráulica en México*, Vol. XXII.
- Baró-Suárez, J; Díaz-Delgado, C; Esteller-Alberich, M; (2007). 'Flood damage curves in residential and agricultural areas of Mexico. Part II: Case study in Lerma River

References

- catchment'. *Ingeniería hidráulica en México*, Vol. XXII.
- Bathurst, J.C.; Ewen, J; Parkin, G; O'Connell, P.E; Cooper, J.D; 2004. Validation of catchment models for predicting land-use and climate change impacts: Blind validation for internal and outlet responses. *Journal of Hydrology*. Vol. 287
- Boyle, S.; Tsanis, I.; Kanaroglou, P.; (1998) 'Developing Geographic Information Systems for Land Use Impact Assessment in Flooding Conditions', *Journal of Water Resources Planning and Management*, Vol. 124.
- Brandt, S. (2005). Resolution issues of elevation data during inundation modeling of river floods. *Proceedings of the XXXI IAHR Congress*.
- Brooks, K. N., Folliott, P. F., & Magner, J. A.; (2013). 'Hydrology and the Management of Watersheds' (4th ed.). *John Wiley & Sons, Inc.*
- Brutsaert, W. (2005). 'Hydrology: an introduction'. *Cambridge University Press*.
- Butts, M; Payne, J; Kristensen, M; Madsen, H; (2004), An evaluation of the impact of model structure on hydrological modelling uncertainty for streamflow simulation, *Journal of Hydrology*, Vol. 298.
- California Government, (2016), <http://www.water.ca.gov/floodsafe/ca-flood-preparedness/fpw-day1.cfm>
- Carabias, J. and Landa, R; (2005) 'Agua, medio ambiente y sociedad, Hacia la gestión integral de los recursos hídricos en México', *Universidad Nacional Autónoma de México, El Colegio de México, Fundación Ríos Arrote, México*.
- Carrillo, N.; (1969). 'The sinking of Mexico City and Proyect Texcoco', *VII International Congress of Soil Mechanics, SHCP editions*.
- Chandra and Ahsa; (2009). 'Rapid flood hazard mapping for catchments in Whangarei and its application'.
- Charlton, M. E., Large, A. R. G., & Fuller, I. C. (2003). 'Application of airborne LiDAR in river environments: the River Coquet, Northumberland, UK'. *Earth Surface Processes and Landforms*.

References

- Chaubey, I., Haan, C. T., Grunwald, S., & Salisbury, J. M. (1999). 'Uncertainty in the model parameters due to spatial variability of rainfall'. *Journal of Hydrology*, Vol. 220.
- Chow, V. . (1972). 'Hydrologic modelling'. *Journal of the Boston Society of Civil Engineering*, Vol. 60.
- CENAPRED (2002). 'Warning Systems Hydro-meteorological in Acapulco, Tijuana, Motozintla, Tapachula and Monterrey, Mexico'. *Technical Report*,
- CENAPRED. (2006) *Seminar-Workshop: Risk reduction in the occurrence of natural disasters in Latin America and the Caribbean., Mexico DF*
- CENAPRED (2006). 'Basic Guide for the Preparation of State and Municipal Atlas of Hazard and Risk', *Hydro-meteorological phenomena*.
- Cloke, H.L. and Pappenberger, F; (2009) 'Ensemble flood forecasting: A review', *Journal of Hydrology*.
- Cochrane, H. C.(1997), 'Forecasting the Economic Impact of a Midwest Earthquake. Economic Consequences of Earthquakes: Preparing for the Unexpected'. *B. G. Jones. Buffalo, USA, National Center for Earthquake Engineering Research*.
- Cochrane, H. C. (2004), 'Economic loss: myth and measurement'. *Disaster Prevention and Management*.
- Cunderlik, J. (2003). 'Hydrologic model selection for the CFCAS project: Assessment of Water Resources Risk and Vulnerability to Changing Climatic Conditions'. *Department of Civil and Environmental Engineering, The University of Western Ontario*.
- National water comission (CONAGUA), (2011), 'Riesgos de inundación en México, Tercer Seminario Internacional de Potamología', *CONAGUA, Mexico*
- Chu, H.-J., Chen, R.-A., Tseng, Y.-H., & Wang, C.-K. (2014). 'Identifying LiDAR sample uncertainty on terrain features from DEM simulation'. *Geomorphology*, Vol. 204.
- CNA (Mexico water comission), (2011), *Manual for flood control, conagua.gob.mx*.
- CNA, (2012) 'Water atlas of Mexico', *SEMARNAT, México*.

References

- Cook, A.; Merwade, V; (2009) Effect of topographic data, geometric configuration and modeling approach on flood inundation mapping, *Journal of Hydrology*, Vol 377.
- Daily mail, 2010: http://i.dailymail.co.uk/i/pix/2013/08/26/article-0-1B67F5E6000005DC-486_1024x615_large.jpg
- DeVantier ,B; Feldman, A.; (1993), '*Review of GIS applications*'
- Durazo, J., and R.N.Farvolden. (1989). 'The ground water regime of the Valley of Mexico from historic evidence and field observations'. *Journal of Hydrology*, Vol. 112.
- DHI, M. b. (2012), *MIKESHE User Manual*.
- DHI, (2009), MIKE 11, *User Guide*
- Dingman, S. L. (2002). Physical hydrology.
- Dutta, D; Herath, S; Musiake, K; (2003) 'A mathematical model for flood loss estimation', *Journal of Hydrology*, Vol. 277.
- Economic Commission for Latin America and the Caribbean (ECLAC), World Bank. (2003), *Handbook for Estimating the Socio-economic and Environmental Effects of Disasters*.
- Ferraris, L; Rudari, R; Siccardi, F; (2002), 'The Uncertainty in the Prediction of Flash Floods in the Northern Mediterranean Environment', *Journal of Hydrometeorology*.
- Filipova, V; Rana, A; Singh, P; (2012) 'Urban flooding in Gothenburg- A MIKE 21 study', *Journal of Water Management and Research*, Vol. 68.
- Floodlist, (2016) <http://floodlist.com/insurance/uk/uk-flash-floods-highlight-need-business-flood-insurance-cover-says-rms>
- Gesch, D., Oimoen, M., Greenlee, S., Nelson, C., Steuck, M., & Tyler, D. (2002). 'The national elevation dataset'. *Journal of the American Society for Photogrammetry and Remote Sensing*, Vol. 68.
- Google, INEGI, (2016), <https://goo.gl/maps/pfxUpGWeBxN2>
- Golden Software, (2002), *Surfer 8, User's Guide*.

References

- Goovaerts, P; (2000). 'Geostatistical approaches for incorporating elevation into spatial interpolation of rainfall', *Journal of Hydrology*.
- Goppert, H; Ihringer, J; Plate, E; Morgenschweis, G., 'Flood forecast model for improved reservoir management in the Lenne River catchment, Germany', (1998), *Hydrological Sciences Journal*, Volume 43.
- Guinot, V, Gourbesville. P (2003) 'Calibration of physically based models: back to basics?.' *Journal of Hydroinformatics*, Vol 5.
- Haile, A., & Rientjes, T. (2005). 'Effects of LiDAR DEM resolution in flood modelling: a model sensitivity study for the city of Tegucigalpa, Honduras'.
- Hall, J; Tarantola, S; Bates, P; Horritt, M; (2005) , 'Distributed Sensitivity Analysis of Flood Inundation Model Calibration', *Journal of Hydraulic engineering*, Vol. 131.
- Hanna, F; Kennedy, R; (1938), The design of dams, 2nd edition,.
- IHDP, (2005), 'Science Plan - Urbanization and Global Environmental Change'. *IHDP Report No. 15*.
- Instituto Nacional de Estadística y Geografía – INEGI, (2010), 'Red hidrográfica escala 1:50,000', 2nd edition, 'Subcuenca hidrográfica rh26dd r. san juan /cuenca r. moctezuma /r.h. pánuco', *Instituto Nacional de Estadística y Geografía - INEGI*.
- Instituto Nacional de Estadística y Geografía, (INEGI) (2010), Online: <http://www.beta.inegi.org.mx/app/mapa/inv/>
- International risk governance council, (2005), 'Risk governance: towards an integrative approach', *IRGC*.
- Jha, A; Bloch R; Lamond, J; (2012) 'Cities and Flooding A Guide to Integrated Urban Flood Risk Management for the 21st Century', *The Global Facility for Disaster Reduction and Recovery (GFDRR)*, *The World Bank*.
- Jonkman, S.N.; Bočkarjovab, M; Kokc, M; Bernardinid, P; (2008). 'Integrated hydrodynamic and economic modelling of flood damage in the Netherlands', *Ecological economics*, Vol. 66.

References

- Klein R.J.T., Smit M.J., Goosen H., and Hulsbergen C.H. (1998). 'Resilience and Vulnerability: Coastal Dynamics or Dutch Dikes?', *The Geographical Journal*, Vol. 164
- Klemeš, V. (1989). 'The improbable probabilities of extreme floods and droughts.' *Hydrology of disasters*, London: James and James.
- Klemes, V; (1993). 'Probability of extreme hydrometeorological events - a different approach.' *Extreme Hydrological Events: Precipitation, Floods and Droughts*.
- Kristensen, K.J; Jensen, S.E; (1975), 'A model for estimating actual evapotranspiration from potential evapotranspiration'. *Nordic Hydrology*, Vol. 6.
- Kundzewicz, Z; Szamalek, K; Kowalczak, P; (1999) 'The Great Flood of 1997 in Poland', *Hydrological Sciences Journal*, Vol. 44
- Kunreuther, H; (1996), 'Mitigating Disaster Losses through Insurance Center for Risk Management and Decision Processes', *Journal of Risk and Uncertainty*, Kluwer Academic Publishers, Wharton School, University of Pennsylvania Philadelphia, PA.
- Legorreta, J. (2005), 'Recent flooding impacts in Distrito Federal', *Agua, La Jornada, Edición Especial*, México.
- Lesser, J.M; Cortes, M.A.; (1998), 'The sinking of the terrain of Mexico City and its implications on the drainage system'; *Ingeniería hidráulica en México*.
- Linsley, R. K., Kohler, M. A., & Paulhus, J. L. H. (1949). 'Applied hydrology'. *McGraw-Hill New York*.
- Luege, J.L.; (2012). 'Hidrological sustainability program', *IV International Legal Colloquium on Water*, CONAGUA, México.
- Maeck, A.; DelSontro, T; McGinnis, D; (2013) 'Sediment Trapping by Dams Creates Methane Emission Hot Spots', *Environmental science technology*.
- Manfreda, S; Di Leo, M; Sole, A; (2011), 'Detection of Flood-Prone Areas Using Digital Elevation Models', *Journal of hydrologic engineering*.
- McCowan, A; Rasmussen, E; Berg, P; (2001) 'Improving the Performance of a Two-dimensional Hydraulic Model for Floodplain Applications', *Australia Conference on Hydraulics in Civil Engineering*, The Institution of Engineers.

References

- Merz, B., Hall, J., Disse M. and Schumann, A. (2010). 'Fluvial flood risk management in a changing world.' *Natural Hazards and Earth System Sciences*. Vol. 10
- Messner, F.; Penning-Rowsell, E.; Green, C; Meyer, V; Tunstall, S; Van der Veen, A; (2007). 'Evaluating flood damages: guidance and recommendations on principles and methods'.
- Middelkoop, H; Daamen K; Gellens, D; Grabs, W; Kwadijk, J; Land, H; Parmet, B; Shaddler, B; Wilke, K; (2001) 'Impact Of Climate Change On Hydrological Regimes And Water Resources Management In The Rhine Basin', *Climatic Change*, Vol. 49
- Milenio newspaper online, (2016): www.milenio.com/df/asentamientos_irregulares-PAOT-viviendas-delegaciones-DF_0_353365029.html.
- Moon, J., Srinivasan, R., & Jacobs, J. H. (2004). 'Stream flow estimation using spatially distributed rainfall in the Trinity River basin, Texas'. *Transactions of the ASAE*, Vol. 47.
- Nascimento, N; M. Baptista; Silva, M; Machado, J; Costa de Lima, M; Gonçalves, A; Silva, R; Dias, É; (2006) 'Flood-damage curves: Methodological development for the Brazilian context', *Water Practice & Technology*.
- National Academy of Sciences (NAS); (1995). 'Mexico City's Water Supply: Improving the outlook for sustainability', *National Academy Press, Washington D.C.*
- National Oceanic and Atmospheric administration (2015): <http://oceanservice.noaa.gov/facts/lidar.html>
- Neodata, (2016): <http://neodata.mx/page/costos-parametricos>
- Newsweek, (2016): <http://www.newsweek.com/pakistan-kashmir-flash-floods-53-dead-443554>
- Ng, H. Y. F., & Marsalek, J. (1992). 'Sensitivity of streamflow simulation to changes in climatic inputs'. *Nordic Hydrology*.
- Norheim, R; Queija, V; and Haugerud, R; (2002), 'Comparison of LIDAR and INSAR DEMs with dense ground control', *Proceedings of the XIXth Congress of the ISPRS, Amsterdam*, Vol. 33.

References

- Organization of American States and the Government of Ireland. (2001). *Manual for the design and implementation of an early warning system for floods in small basins*. Washington, D.C
- Pappenberger, F; (2005), 'Physically based flood models', *Internal Report*.
- Penning-Rowsell, E.C.; Chatterton, J.B; (1977). 'The benefits of flood alleviation. A manual of assessment techniques', *Belhaven Technical Press, London*.
- Penning-Rowsell, E. C, Johnson, C; Tunstall, S; Tapsell, S; Morris; J; Chatterton, J; Cooker, A; Green, C; (2003), 'The benefits of flood and coastal defence: techniques and data for 2003', *Flood hazard research centre, Middlesex University*
- Plate, E.J; 'Flood risk and flood management', (2002) *Journal of Hydrology*, Vol. 267.
- Queensland Government, State of Queensland, (2002), 'Guidance on the assessment of flood damages', *Department of Natural Resources and Mines*.
- Read, Sturgess and Associates (2000). 'Rapid assessment Method (RAM) for Floodplain Management'. *Report to Department of Natural Resources & Environment, Victoria Australia*.
- Refshaard, J. C., Storm, B., & Singh, V. P. (1995). 'MIKE SHE. Computer Models of Watershed Hydrology'. Pg. 809–846.
- Renn, O.; (1992), Concepts of risk: A classification', *Praeger*, Westport, Conn.
- Sayers P., Gouldby B.P., Simm J.D., Meadowcroft I. and Hall J. (2003). 'Risk, Performance and uncertainty in flood and coastal defence – A review'. *R&D Technical report FD2302/TR1*.
- Saksena, Siddharth; (2014). 'Investigating the role of DEM resolution and accuracy on flood inundation mapping'. *A Thesis Submitted for the Degree of Master of Science in Civil Engineering, Purdue University, Indiana*.
- Sanders, B. F. (2007). 'Evaluation of on-line DEMs for flood inundation modeling'. *Advances in Water Resources*.

References

- Segond, M.L.; Wheeler, H; Onof, C; (2007). 'The significance of spatial rainfall representation for flood runoff estimation', *Journal of Hydrology*.
- SEMARNAP, (1997), 'National report of the UN climate change conference', *Enkidu Editores, México*.
- Sendzimir J., Magnuszewski P., Flachner Z., Balogh P., Molnar G., Sarvari A. and Nagy Z. (2007). 'Assessing the resilience of a river management regime: informal learning in a shadow network in the Tisza River Basin'. *Ecology and Society*.
- SMA-DF (2006), 'Strategy for climate in Distrito Federal'. *Secretaría de Medio Ambiente del Distrito Federal, México*.
- Smith, D; (1994) 'Flood damage estimation: A review of urban stage-damage curves and loss functions', *Centre for resource and environmental studies, Australian National University*.
- Smith, K; Ward, R; (1998), *Floods, Physical Processes and Human Impacts*.
- Tate, E., & Maidment, D. (1999). *Floodplain mapping using HEC-RAS and ArcView GIS*.
- UNISDR (United Nations International Strategy for Disaster Reduction). (2004). 'Guidelines for Reducing Flood Losses.' Geneva: UNISDR. http://www.unisdr.org/files/5353_PR200402WWD.pdf.
- United Nations, (2006), EWC III. 'Developing Early Warning Systems', *Third International Conference on Early Warning, Bonn, Germany*
- U.S. Corps of engineers (USACE), (1992) 'Catalog for residential depth damage functions', *USACE*,
- USDA,(2010);www.nrcs.usda.gov/technical/stream_restoration/Images/scriimage/chap3/fig3-21.jpg
- UNU-EHS (2012), 'World risks report'. *United Nations University, Institute for environment and human security*.
- Van de Sande, B; Lansen, Joost; Hoyng, C; (2012), 'Sensitivity of Coastal Flood Risk Assessments to Digital Elevation Models', *Water*.

References

- Vansteenkiste, T., Tavakoli, M., Van Steenberghe, N., De Smedt, F., Batelaan, O., Pereira, F., & Willems, P. (2014). 'Intercomparison of five lumped and distributed models for catchment runoff and extreme flow simulation'. *Journal of Hydrology*, Vol. 511.
- Vazquez, R.F; Feyen, L.; Feyen, J.; Refsgard, J.C.; (2002). 'Effect of grid size on effective parameters and model performance of the MIKE SHE code', *Hydrological processes*.
- Vis M., Klijn F., de Bruijn K.M. and Buuren M. van (2003). 'Resilience strategies for flood risk management in the Netherlands'. *International journal of river basin management*.
- Walker, B., Holling, C.S., Carpenter, S.R. and Kinzig, A. (2004). 'Resilience, adaptability and transformability in social–ecological systems'. *Ecology and Society*, [online] URL: <http://www.ecologyandsociety.org/vol9/iss2/art5/>
- Ward, R; Robinson, M; (2000), *Principles of Hidrology, 4th Edition, MCGRaw Hill*.
- Werner, M. G. (2001). 'Impact of grid size in flood mapping using 1-d flow GIS-Based model', *Physics and Chemistry of Earth, Part B: Hydrology, Oceans and Atmosphere*.
- Werner, M; Reggiani, P; De Roo, A; Bates, P; and Sprokkereef, E; (2005), 'Flood Forecasting and Warning at the River Basin and at the European Scale', *Natural hazards*.
- Villordon (2014), 'Community-Based Flood Vulnerability Index for Urban Flooding: Understanding Social Vulnerabilities and Risks', Thesis, *Universite de Nice, France*.
- Vargas, R; Gourbesville, P; (2014), Deterministic hydrological model for flood risk assessment of mexico city, *SimHydro conference, Sophia Antipolis, France*.
- Vo, N.D, Gourbesville, P. (2014). 'Rainfall uncertainty in distributed hydrological modelling in large catchments: an operational approach applied to the vu gia-thu bon catchment - Viet Nam'. *3rd IAHR Europe Congress, Book of Proceedings*.
- Wikimapia, (2013), <http://wikimapia.org/4239661/es/Colonia-las-Gaviotas-Norte-y-Sur>
- Wikimedia, (2012), https://upload.wikimedia.org/wikipedia/commons/9/90/MX-DF-Crecimiento_de_la_ciudad_de_México.png

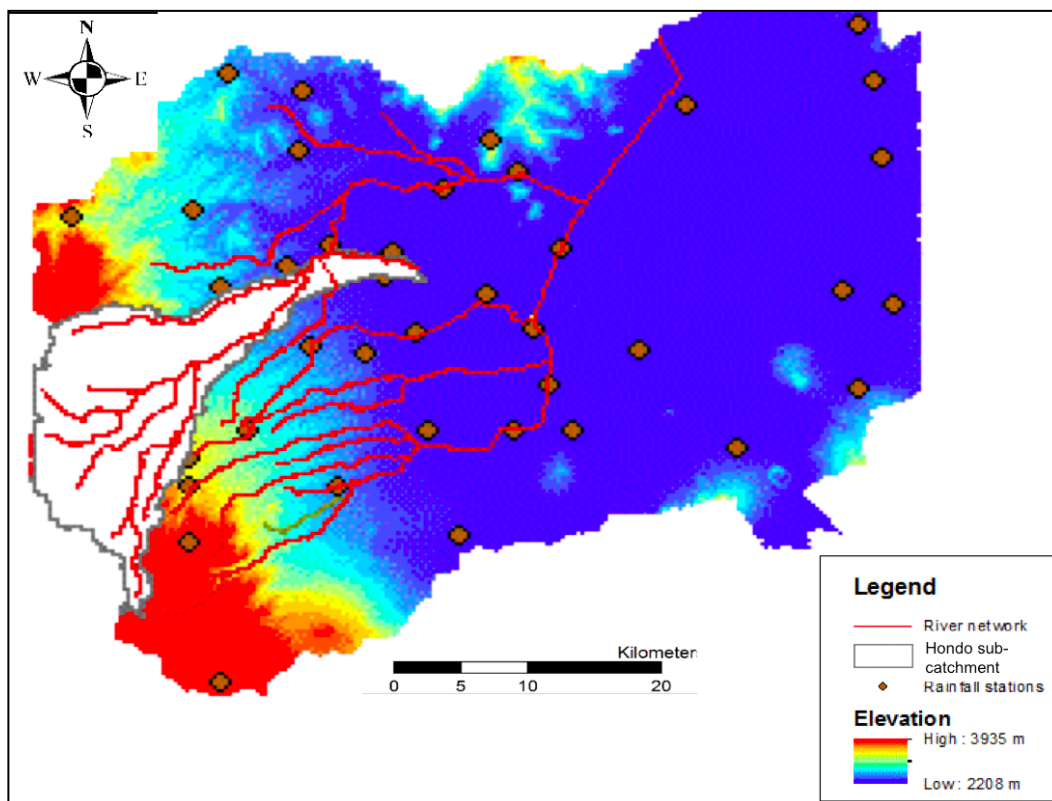
References

- Wittwer, C. (2013). 'WMO/UNESCO-IHP guideline for flood forecasting'. *In Regional Workshop on hydrological forecasting and impact of climate change on water resources. Pržno/Budva, Montenegro.*
- World Meteorological Organization (WMO) and Global Water Partnership (GWP), (2013), 'Integrated Flood Management Tools Series No.20'.
- Xu, C. (2002). 'Hydrologic models'. *Textbooks of Uppsala University. Department of Earth Sciences Hydrology.*
- Zandbergen, P; (2006), 'The effect of DEM cell resolution on depressions in digital elevation models'. *Applied GIS.*

APPENDIX

Appendix I. Climatological stations.

In this annex, the rainfall gauging stations used in this study will be presented. These are seen in the figure bellow, which includes the river network, and elevation.



Rainfall stations and evaporation stations in red.

The following table shows the names of each of the climatological stations used, the authority in charge of them, the altitude and their geographic location.

Appendix

Station code	Name	Municipality	State	Sub-basin	Authority	Alt.	Long	Lat
00009043	SAN JUAN DE ARAGON	GUSTAVO A. MADERO	DISTRITO FEDERAL	LAGO DE TEXCOCO Y ZUMPANGO	CONAGUA-DGE	2240.0	-99.079	19.46527778
00009026	MORELOS 77	IZTAPALAPA	DISTRITO FEDERAL	LAGO DE TEXCOCO Y ZUMPANGO	CONAGUA-DGE	2240.0	-99.083	19.36666667
00009052	UNIDAD MODELO	IZTAPALAPA	DISTRITO FEDERAL	LAGO DE TEXCOCO Y ZUMPANGO	CONAGUA-DGE	2259.0	-99.116	19.36666667
00009054	GENERAL ANAYA	BENITO JUAREZ	DISTRITO FEDERAL	LAGO DE TEXCOCO Y ZUMPANGO	CONAGUA-DGE	2240.0	-99.166	19.36666667
00009036	PLAYA CALETA 454 COLONIA MARTE	IZTACALCO	DISTRITO FEDERAL	LAGO DE TEXCOCO Y ZUMPANGO	CONAGUA-DGE	2235.0	-99.097	19.39527778
00009038	PRESA MIXCOAC	ALVARO OBREGON	DISTRITO FEDERAL	LAGO DE TEXCOCO Y ZUMPANGO	CONAGUA-DGE	2240.0	-99.2666	19.36666667
00009010	COLONIA AMERICA	MIGUEL HIDALGO	DISTRITO FEDERAL	LAGO DE TEXCOCO Y ZUMPANGO	CONAGUA-DGE	2271.0	-99.201	19.4125
00009015	RODANO 14 (CFE)	CUAUHTEMOC	DISTRITO FEDERAL	LAGO DE TEXCOCO Y ZUMPANGO	CFE	2250.0	-99.173	19.425
00009013	COLONIA MOCTEZ	VENUSTIANO CARRANZA	DISTRITO FEDERAL	LAGO DE TEXCOCO Y ZUMPANGO	CONAGUA-SMN	2235.0	-99.105	19.42777778

Appendix

	UMA	A	AL	ZUMPANGO				
00009 033	COLONIA GUERRERO	CUAUHTE MOC	DISTRI TO FEDER AL	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-DGE	2237 .0	-99.133	19.45
00009 047	COLONIA TACUBA	MIGUEL HIDALGO	DISTRI TO FEDER AL	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-SMN	2255 .0	-99.189	19.459 72222
00009 021	EGIPTO 7	AZCAPOT ZALCO	DISTRI TO FEDER AL	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-DGE	2247 .0	-99.186	19.475
00009 025	HACIEND A LA PATERA	GUSTAVO A. MADERO	DISTRI TO FEDER AL	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-DGE	2240 .0	- 99.1583	19.512 77778
00009 029	GRAN CANAL KM. 6+250	GUSTAVO A. MADERO	DISTRI TO FEDER AL	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-DGE	2239 .0	-99.091	19.476 66667
00009 067	MONTE ALEGRE	LA MAGDALE NA CONTRER AS	DISTRI TO FEDER AL	RIO ALMOLOYA- OTZOLOTEP EC	CONAGU A-DGE	3450 .0	-99.283	19.216 66667
00009 019	DESIERT O DE LOS LEONES	ALVARO OBREGON	DISTRI TO FEDER AL	RIO ALMOLOYA- OTZOLOTEP EC	CONAGU A-DGE	2220 .0	-99.389	19.3
00009 014	COLONIA SANTA URSULA COAPA	COYOACA N	DISTRI TO FEDER AL	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-DGE	2256 .0	-99.148	19.303 33333
00009 016	CUAJIMA LPA	CUAJIMAL PA DE MORELOS	DISTRI TO FEDER AL	RIO ALMOLOYA- OTZOLOTEP EC	CONAGU A-SMN	2283 .0	-99.334	19.35

Appendix

00009 030	LA VENTA CUAJIMA LPA (SMN)	CUAJIMAL PA DE MORELOS	DISTRI TO FEDER AL	RIO ALMOLOYA- OTZOLOTEP EC	CONAGU A-SMN	2850 .0	-99.367	19.333 33333
00009 037	PRESA ANSALD O	LA MAGDALE NA CONTRER AS	DISTRI TO FEDER AL	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-DGE	2363 .0	-99.216	19.333 33333
00015 033	HUIXQUI LUCAN	HUIXQUIL UCAN	MEXIC O	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-DGE	2680 .0	-99.350	19.361 11111
00015 050	LOS REYES	LA PAZ	MEXIC O	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-DGE	2248 .0	- 98.9916	19.357 77778
00015 023	CHIMALH UACAN	CHIMALHU ACAN	MEXIC O	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-DGE	2330 .0	-98.922	19.391 38889
00015 061	NEZAHU ALCOYO TL	NEZAHUA LCOYOTL	MEXIC O	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-DGE	2278 .0	-99.045	19.415 83333
00015 209	PRESA SAN JOAQUIN	HUIXQUIL UCAN	MEXIC O	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-DGE	2330 .0	-99.233	19.416 66667
00015 167	EL TEJOCO TE	TEXCOCO	MEXIC O	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-DGE	2485 .0	-98.902	19.443 33333
00015 145	PLAN LAGO DE TEXCOC O	CHIMALHU ACAN	MEXIC O	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-DGE	2260 .0	-98.931	19.450 55556
00015 077	PRESA TOTOLIC A	NAUCALP AN DE JUAREZ	MEXIC O	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-DGE	2385 .0	-99.283	19.452 77778
00015 127	TOTOLIC A SAN BARTOL	NAUCALP AN DE JUAREZ	MEXIC O	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-DGE	2325 .0	-99.245	19.465 55556

Appendix

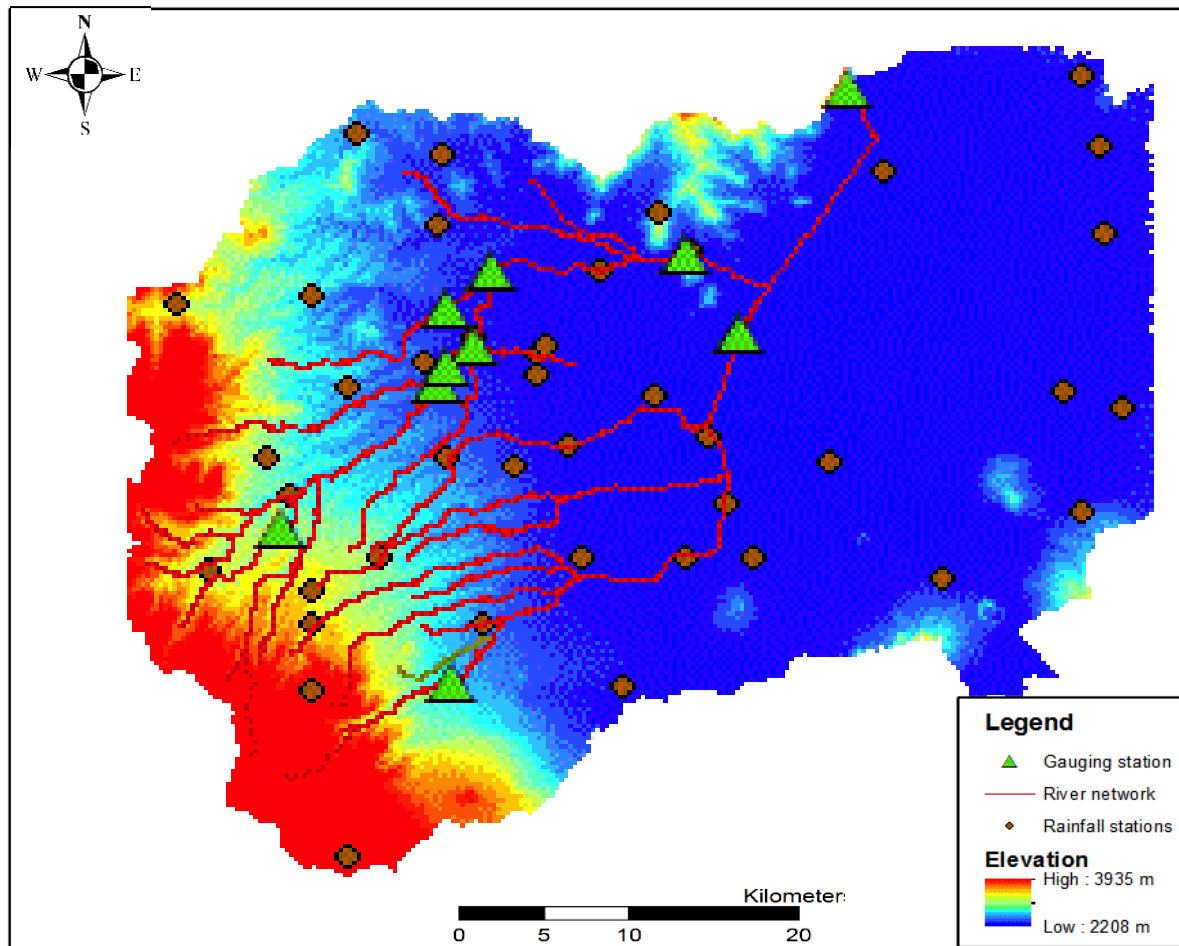
	O							
00015 095	SAN LUIS AYUCAN	JILOTZING O	MEXIC O	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-DGE	2755 .0	-99.367	19.495 27778
00015 027	EL SALITRE	NAUCALP AN DE JUAREZ	MEXIC O	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-DGE	2480 .0	-99.378	19.5
00015 059	MOLINO BLANCO	NAUCALP AN DE JUAREZ	MEXIC O	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-DGE	2226 .0	-99.220	19.477 5
00015 083	SAN ANDRES	TEXCOCO	MEXIC O	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-DGE	2244 .0	-98.910	19.531 94444
00015 092	SAN JUAN IXHUATE PEC	TLALNEPA NTLA DE BAZ	MEXIC O	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-DGE	2260 .0	-99.114	19.521 66667
00015 013	CALACO AYA	ATIZAPAN DE ZARAGOZ A	MEXIC O	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-DGE	2281 .0	-99.239	19.534 16667
00015 041	GRAN CANAL KM 27+250	ECATEPE C DE MORELOS	MEXIC O	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-DGE	2242 .0	-99.019	19.561 66667
00015 044	LA GRANDE	ATENCO	MEXIC O	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-DGE	2250 .0	- 98.9139	19.576 11111
00015 075	PRESA LAS RUINAS	ATIZAPAN DE ZARAGOZ A	MEXIC O	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-DGE	2360 .0	-99.278	19.581 11111
00015 100	SAN MATEO TECOLO APAN	ATIZAPAN DE ZARAGOZ A	MEXIC O	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-DGE	2285 .0	- 99.2375	19.570 83333
00015 124	TEPEXP AN	ACOLMAN	MEXIC O	RIO ATLACOMUL	CONAGU A-DGE	2248 .0	-98.921	19.611 38889

Appendix

				CO-PASO DE OVEJAS				
00015 040	GRAN CANAL KM 02+120 BOMBAS	ECATEPE C DE MORELOS	MEXIC O	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-DGE	2250 .0	-99.068	19.609 72222
00015 041	GRAN CANAL KM 27+250	ECATEPE C DE MORELOS	MEXIC O	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-DGE	2242 .0	-99.019	19.561 66667
00015 042	GRAN CANAL KM 46+930	ZUMPANG O	MEXIC O	RIO TEZONTEPE C	CONAGU A-DGE	2245 .0	-99.177	19.8
00015 043	FES CUAUTIT LAN	CUAUTITL AN	MEXIC O	RIO CUAUTITLAN	CONAGU A-SMN	2251 .6	-99.183	19.683 33333
00009 043	SAN JUAN DE ARAGON	GUSTAVO A. MADERO	DISTRI TO FEDER AL	LAGO DE TEXCOCO Y ZUMPANGO	CONAGU A-DGE	2240 .0	-99.079	19.465 27778

Appendix II. Discharge gauging stations.

Bellow, a detailed description of each gauging station used in this study will be presented. The 10 stations and their location in the Mexico City catchment, are depicted in green in the following figure:



Appendix

Sation Name	Current	Drained area (km^2):	Long (D,M,S)	Lat D,M,S)	Objective
MOLINO BLANCO	RIO DE LOS REMEDIOS	203.1	99°, 13", 15'	19°, 28", 39' Long	To know the volume of entrance to the reservoir.
EL MOLINITO	Río Hondo	143.1	99°, 14", 08'	19°, 27", 13'	Know the discharge of river Hondo in this place for hydrological studies
SAN JUAN IXHUATEPEC	Rio Remedios.	N/A	99°, 07", 07'	19°, 31", 15'	Determine the volumes before discharging in the Grand Canal.
PUENTE DE VIGAS	Rio Remedios	336.7	99°, 12", 40'	19°, 30", 42'	Quantify the extractions and exceedents of El Cristo reservoir
SAN BARTOLITO	Río Borracho	106.0	99°, 17", 36'	19°, 23", 54'	Quantify volumes in río Borracho, downstream of its confluence with the Ajolotes river.
KM. 6 +250	Grand Canal	N/A	99°, 05", 29'	19°, 28", 36'	Quantify the volume in the Grand Channel in its initial section, before receiving the volumes of the Dales Channel, la Draga and the Lake of Texcoco.
SAN LUCAS	RIO DE LA COMPAÑIA	293.5	98°, 51", 25'	19°, 17", 05'	Measure the hydric potential of the river La Compañía, for hydrological studies for

Appendix

					irrigation
ETCHEGARAY	Rio Chico de los Remedios	36.4	99°, 14", 00'	19°, 28", 50'	Quantify the discharge to El Cristo reservoir.
CALACOAYA III	Río Tlalnepantla	N/A	99°, 15", 19'	19°, 31", 30'	Quantify the volumes corresponding to the sweage and rainfall waters from the area near the Madin Dam.
SANTA TERESA	Río Magdalena	30.0	99°, 14", 10'	19°, 18", 10'	Quantify the volumes and discharges in River Magdalena for hydrological studies.

Appendix III. Code for converting from .sdf to .xns11 (HEC-RAS to MIKE 11) for cross section data. (Created by Vo Ngoc Duong, The University of Da Nang)

```
import java.io.BufferedReader;
import java.io.File;
import java.io.FileNotFoundException;
import java.io.FileReader;
import java.io.FileWriter;
import java.io.IOException;
import java.io.PrintWriter;
import java.util.StringTokenizer;

public class Converting {
    private double a0, a, b0, b, c;
    private ReadData data;
    private WriteNewData newData;

    public Converting(String sourceText, String newText) {
        // Load data
        data = new ReadData(sourceText);

        // Write new data
        newData = new WriteNewData(newText);
    }

    // Base on  $\sqrt{\text{power2}(a1-a)+\text{power2}(b1-b)}$ 
    public void process() {
        // each line in sourceData
        String line = "";
        double stationNumber = 0;
```

```
// read & process each line
while ((line = data.getLine()) != null) {
    // Get STATION number
    if (line.contains("STATION:")) {
        stationNumber = Double.valueOf(line.substring(9));
    }
    // Get position of line "SURFACE LINE:"
    // Set a & b values
    // Write (new) header
    if (line.contentEquals("SURFACE LINE:")) {
        WriteNewData tempData = new WriteNewData("data.tmp");
        int profileNumber = 0;
        // save data needed to convert to a temp file
        while (!(line = data.getLine()).equalsIgnoreCase(""))
            || line.equalsIgnoreCase("END:")) {
            tempData.WriteLine(line);
            profileNumber++;
        }
        tempData.close();
        converting("data.tmp", profileNumber, stationNumber);
    }
}

// Done
close();
}

// Write (new) header
private void WriteHeader(double stationNumber) {
```

```
        newData.WriteLine("Topo?");
        newData.WriteLine("N6");
        newData.WriteLine("      " + stationNumber);
        newData.WriteLine("COORDINATES");
        newData.WriteLine("  0");
        newData.WriteLine("FLOW DIRECTION");
        newData.WriteLine("  0");
        newData.WriteLine("PROTECT DATA");
        newData.WriteLine("  0");
        newData.WriteLine("DATUM");
        newData.WriteLine("  0");
        newData.WriteLine("RADIUS TYPE");
        newData.WriteLine("  0");
        newData.WriteLine("DIVIDE X-Section");
        newData.WriteLine("0");
        newData.WriteLine("SECTION ID");
        newData.WriteLine("");
        newData.WriteLine("INTERPOLATED");
        newData.WriteLine("  0");
        newData.WriteLine("ANGLE");
        newData.WriteLine("  0.00  0");
        newData.WriteLine("RESISTANCE NUMBERS");
        newData.WriteLine("  1  0    1.000    1.000    1.000    1.000    1.000");
    }
    //
    private void setA0B0(String line) {
        StringTokenizer token = new StringTokenizer(line, ",");
```

```
double[] elements = new double[3];
int i = 0;
while (token.hasMoreElements()) {
    elements[i] = Double.valueOf(token.nextToken());
    i++;
}
// set values
a0 = elements[0];
b0 = elements[1];
}

// Converting data
private void converting(String fileTmp, int profileNumber, double stationNumber) {
    String line;
    // Write (new) header
    WriteHeader(stationNumber);
    newData.WriteLine("PROFILE      " + profileNumber);
    ReadData tmpData = new ReadData(fileTmp);
    tmpData.getLine();
    // process next line
    setA0B0(line = tmpData.getLine());
    while (line != null) {
        converting(line);
        line = tmpData.getLine();
    }
    tmpData.Close();
    newData.WriteLine("*****");
}
```

```
}  
  
// Line processing  
private void converting(String line) {  
    StringTokenizer token = new StringTokenizer(line, ",");  
    double[] elements = new double[3];  
    int i = 0;  
    while (token.hasMoreElements()) {  
        elements[i] = Double.valueOf(token.nextToken());  
        i++;  
    }  
    double convertedValue = Math.sqrt(Math.pow(elements[0] - a0, 2)  
        + Math.pow(elements[1] - b0, 2));  
    newData.WriteLine(convertedValue + " " + elements[2] + " 1    <#0>");  
}  
  
// Finish the stuff  
private void close() {  
    data.Close();  
    newData.close();  
    System.out.println("Converting done !");  
}  
}
```