Chapter 13

Flood Risk Management in Mexico

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Additional information is available at the end of the chapter

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Abstract

Mexico receives an average annual rainfall of 740 mm, which are distributed in the hydrological cycle as follows: 72% evapotranspiration, 21% becomes runoff and 6% as aquifer recharge. Within the Mexican territory, exist a great diversity of climates and high spatial and temporal variability in water resources availability. In the period 2000–2015, damages from hydrometeorological phenomena in Mexico represented between 60 and 99% of total damages and losses at national level due to natural and socioorganizational events. Considering global climate change impact on the selection, design and implementation of flood control measures, represents a major challenge, since the level of certainty regarding its influence on the variables involved, remains insufficient. This chapter provides a description of the main elements directly linked to flooding in México, such as a high spatial and temporal variability in water resources availability and presence of tropical cyclones in both coasts and climate change. A brief summary of the main disasters caused by hydrometeorological phenomena, the annual cost of the damages, the main non-structural measures for flood control and the intervention from the Mexican Institute of Water Technology in the use, development and spread of technology focused on flood risk management are also included.

Keywords: flood risk, flood risk management, water vulnerability, resilience

1. Introduction

Mexico covers an area of 1.964 million km^2 [14], and its annual average rainfall (1981–2010) is 740 mm, equivalent to 1449 km^3, which are distributed in the hydrological cycle as follows: 72% evapotranspiration, 21% becomes runoff and 6% as aquifer recharge. In addition, every year Mexico receives from the United States and Guatemala 48 km^3 through transboundary watersheds and exports 0.43 km^3 to the United States, based on the 1944 U.S.-Mexico Water Treaty [3].

The population, estimated to be around 119.5 million in 2015, ranks 11th in the world, with a growth rate of 1.4%, and 77% of the Mexican habitants live in urban areas [15]. Population forecast for 2030 shows this trend will be accentuated in the next years. Therefore, it will be an increasing and of water concentrated in metropolitan regions.

Water withdrawals from surface and ground water sources represent 52 and 32.9 km^3/year, respectively. In total, 77% of the water from rivers and groundwater goes into irrigation, whereas 14% is used in domestic applications and 9% for industry [3].

It should be note that 77% of the population that needs to be supplied is located in the north and central region of the country, where only 33% of the water resources are found, which leads to overexploitation of basins and aquifers [3].

Because of its geographic location, varied orography and furthermore the presence of meteorological and climatological phenomena at different scales, Mexico presents a great diversity of climates and high spatial and temporal variability in water resources availability.

2. Climatological and meteorological aspects

Some phenomena that have influence on intensity on intensity, as well as spatial and temporal distribution of precipitation, are severe convective storms, tropical cyclones, cold fronts, easterly waves, seasonal Intertropical Convergence Zone (ITCZ) migration, seasonal variability of jet streams and warming in the tropical regions, also called dynamics of the East Pacific Warm Pool.

Although tropical cyclones contribute to surface and ground water recharge, due to the atmospheric moisture transport from the oceans to the continental regions that increase the rainfall during the tropical cyclone season, **Figure 1**, they also lead to severe damage to exposed and vulnerable population centres affected by floods.

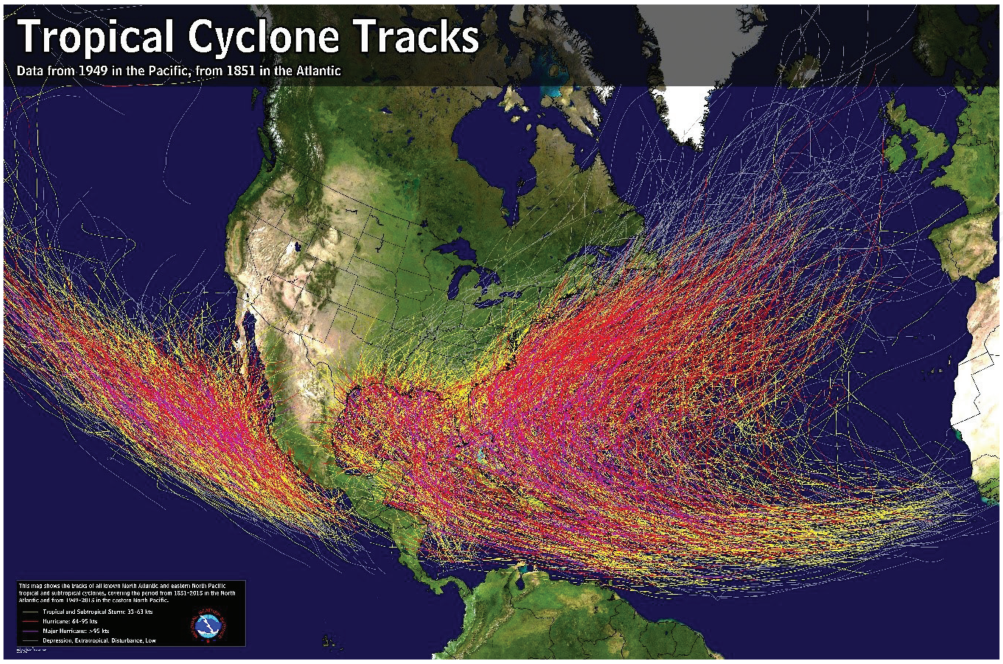

Figure 1. Historical tracks of tropical cyclones, from 1949 to 2015 in the Pacific and 1851 to 2015 in the Atlantic. Source: NOAA [19].

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In Mexico, according to the recorded paths, during the period 2000–2016 in the Pacific Ocean, an average of 17.6 tropical cyclones were generated, an average of 15.4 acquired name and 3.8 made landfall. While, in the Atlantic Ocean during the same period, an average of 15.4 tropical cyclones were generated, an average of 14.8 acquired name and 2.6 made landfall.

Cold fronts also have great influence; they are present between September and May. Their behaviour includes the dragging of cold and humid air masses that can reach as far as the southeast of the country.

3. Climate change impact

Considering global climate change impact on the selection, design and implementation of flood control measures, it represents a major challenge since the level of certainty regarding its influence on the variables involved remains insufficient.

The vulnerability can be defined as the degree to which a system (in this case to water resources) is susceptible to adverse effects, and according to the Intergovernmental Panel on Climate Change (IPCC) on his Fourth Assessment Report, vulnerability depends on degree of exposure, sensitivity and adaptive capacity [16].

Based on this definition, an estimate of the level of the social vulnerability to climate change in Mexico municipalities has been made. The following contains a description of the publication.

3.1. Atlas of Water vulnerability to climate change in Mexico (Mexican Institute of Water Technology, IMTA, 2016)

IMTA coordinates the analysis, updating and publication of climatic scenarios in Mexico, based on the General Circulation Models (GCM) of the Coupled Model Intercomparison Project phase 5 (CMIP5) experiment for the historical period 1961– 2000 and greenhouse gas emission projections denominated Representative Concentration Pathways 6.0 and 8.5 (RCP6.0 and RCP8.5), for two periods of the twenty-first century, from 2015 to 2039 and from 2075 to 2099, **Figure 2**. The Atlas of Water vulnerability to climate change in Mexico includes scenarios of the effect on maximum temperature, minimum temperature, average temperature and precipitation. Furthermore, it includes an estimate of the municipal risk for rainy and tropical cyclone seasons, **Figure 3**.

Maps are one of the most useful tools in flood risk management, since they concentrate and synthesize large amounts of information analysed and processed using a geographic information system. They play a central role in the delineation of floodplains for different return periods, visualization of change in flow depth and velocity, strategic planning, early warning systems, impact analysis on infrastructure and population and damage assessments.

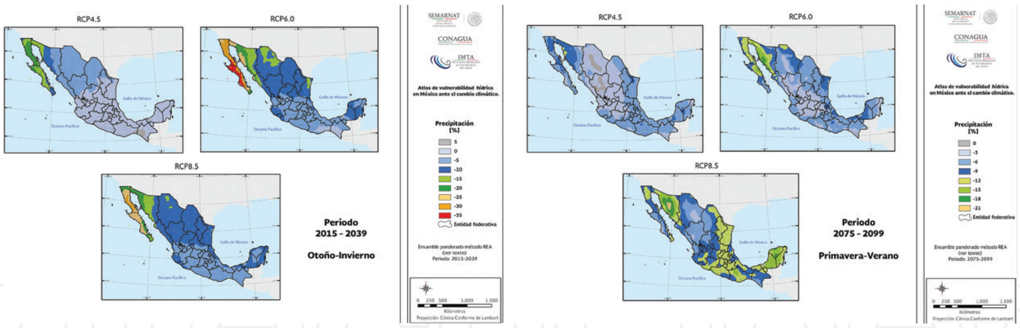

Figure 2. Projected precipitation change for the periods 2015–2039 and 2075–2099, due to climate change. Source: IMTA [13].

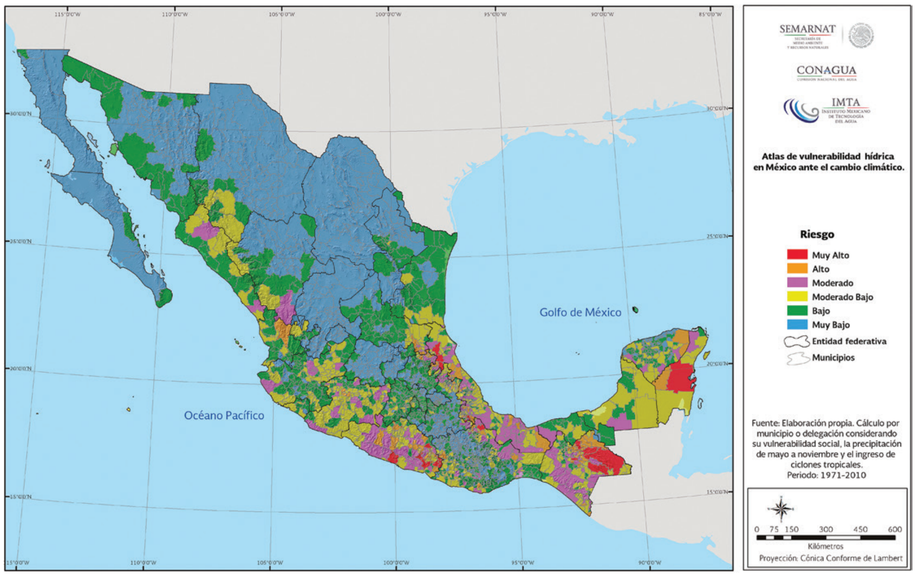

Figure 3. Municipal Risk for rainy and tropical cyclone season in Mexico. Source: IMTA [13].

4. Area susceptible to flooding

The IPCC defines flood as 'the overflowing of the normal confines of a stream or other body of water, or the accumulation of water over areas that are not normally submerged'. Floods include river (fluvial) floods, flash floods, urban floods, pluvial floods, sewer floods, coastal floods and glacial lake outburst floods [16].

Some causes of flooding are precipitation associated with hydrometeorological and climatic phenomena, snowmelt, drainage conditions in watersheds, deforestation, urbanization, poor drainage systems without regular maintenance, inadequate management operation of dam systems, failure of constructed or landslide dams, high tide or some combination of these.

An example of landslide damming of river at risk of failure occurred in 2007 in the Grijalva River, the second largest river in the country by the volume of water it discharges. A wedge

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of rock and clay material, at 55 Mm^3, slid and dammed the stream. The dam was estimated to have a height of 80 m, a length of 800 m and a width of 300 m, located downstream of the Malpaso Dam and upstream the Peñitas Dam. The town of Juan de Grijalva was located on the right bank of the river and was affected by the landslide and the flood wave that followed, both caused the death of 25 people. An estimated volume of 15 mm^3 was filling the Grijalva River valley and creating a landslide dam which impounded the river. The potential risk of failure of this natural dam posed a grave threat to the Peñitas Dam and to more than 3 million downstream inhabitants of cities, such as Villahermosa, Cárdenas, Comalcalco and Huimanguillo (state of Tabasco). The problem was solved by constructing a channel on the material slid, so the river was returned to its natural course.

From the analysis of several floods in Mexico, it has been concluded that long-term heavy rainfall in large basins is associated with river flooding, whereas short-term heavy rainfall in small basins is related to pluvial flooding. The flood management strategies must also consider the presence of debris flow.

The flood problem becomes more complex for the wide range of factors involved and their variability, for example, precipitation intensity is already being influenced by climate change. In addition, inappropriate development policies encourage unplanned urbanization, piping of channels and/or engineering projects that reduce the flow capacity of the rivers.

It has been estimated that 162,000 km^2 of the Mexican territory are susceptible to flooding, see **Figure 4**. Although this accounted for only 8% of its territory, the socio-economic impact may be equivalent up to billions of dollars, according to the affected urban zones, their population density, economic activities, existing infrastructure and, above all, their vulnerability and resilience.

Figure 4. Location and delineation of the main wetlands in Mexico. Source: INEGI [14].

5. Severe floods in Mexico

There is information about floods in the city of Tenochtitlan until 1521 and in New Spain in later years. Since then, structural and non-structural measures for flood control have been adopted. In **Table 1**, some of the worst floods recorded in central Mexico are listed.

Some other major floods are presented in **Table 2**.

Year	Event
1446	First great flood in Tenochtitlán, some sectors of the city were flooded due to heavy rainfall [5]
1449	Tenochtitlán suffered another flood and a 16 kilometer long embankment was constructed [20]
1499	Another flood occurred in Tenochtitlán that covered streets and squares and later reached the lake through the canals. As a result, the water level of the lake raised and it was necessary to build new dykes [17]
1555	On 10th October, intense precipitation began in the Valley of Mexico; after 4 days, people were forced to transport in canoes [17]
1604	The city of Mexico suffered floods that persisted during months, the only way of water removal was by evaporation. It was then decided to build an artificial outlet to drain excess water into the Tula river basin [6]
1607	Heavy rainfall occurred in June in the capital city, which resulted in the most severe flood in the country's capital since the Spanish occupation [17]
1629	Called the Great Flood, it was the most severe in the history of the city. Heavy rains were combined and little progress was made in the construction of the General Drainage of the city, it is estimated that 30,000 people died [6]

Table 1. Floods in central Mexico.

Year	Event
1760	Silao River overflowing caused floods in the city of Guanajuato, with the presence of silt under the bridges that reduced the river capacity [18]
1909	The worst flood recorded in the city of Monterrey as a result of the overflowing of Santa Catarina River that caused the death of 5,000 people [12]
1982	Due to the effect of Hurricane Paul, numerous floods occurred in several cities in the state of Sinaloa [2]
1985	There were 64 floods in 16 states of the Mexican Republic [2]
1988–1992	Flooding in the state of Veracruz left 75,000 victims in 1988; 52,546 in 1989, 129,565 in 1990, 67,470 in 1991 and 60,000 in 1992 [2]
1995	Hurricanes Ismael, Roxanne and Opal affected the states of Tabasco, Campeche, Quintana Roo, Yucatan and Veracruz [2]. Between 1 June and 31 October, in the state of Tabasco, it rained 1792 mm [1]
1997	Hurricane Paulina caused flooding in the states of Chiapas, Oaxaca and Guerrero [2]
1998	The floods affected 29,000 people in Chiapas and there were 4840 people affected in Oaxaca, leaving 700,000 people without electricity [2]

Year	Event
1999	The combination of several meteorological phenomena caused one of the worst floods in the city of Villahermosa, which resulted in the construction of levees around the city and along urban rivers, as well as the implementation of the Comprehensive Flood Control Program (PICI) [1].
2005	In July, Hurricane Emily hit the Atlantic coast of Mexico, Quintana Roo, Yucatán, Tamaulipas and Nuevo León were the most seriously affected states. In October, the states of Quintana Roo and Yucatan were affected by Hurricane Wilma [8]
2007	On 4 October, the city of Tapachula in Chiapas, suffered the worst disaster in its history, as a result of prolonged and heavy rainfall associated with Hurricane Stan [1]
2008	The combined effect of Hurricane Noel and two cold fronts, caused two-thirds of the city of Villahermosa, was flooded during 40 days. Together with the phenomenon of landslide damming of Grijalva River, represent two of the greatest natural disasters in recorded history of Mexico [1]
2010	There were floods in the states of Zacatecas, Chihuahua, Veracruz and Tabasco. In relation to the latter, the PICI Flood Management Plan was redefined, for what would be the future Comprehensive Water Program of Tabasco (PHIT) [1]
2011	This was the second rainiest year in the country, with local flooding in Mexico City and many others due to the effects of hurricanes Alex, Karl and Matthew, the cost of damages exceeded the 4000 mdd [7]
2013	Hurricane Jova affected the states of Colima and Jalisco, whereas Arlene affected the state of Veracruz and the central part of the country and the state of Hidalgo. For the fifth year in a row, the state of Tabasco suffered severe floods [9]
2014	As a result of the incidence of two simultaneous tropical cyclones, Ingrid in the Gulf of Mexico and Manuel in the Pacific Ocean, the state of Guerrero was seriously affected. Besides, hurricane Barbara hit the pacific coast in state of Chiapas [11]
2015	Heavy damage occurred in the state of Veracruz during October. In addition, the state of Tamaulipas and Chihuahua were flooded [10]

Table 2. Major floods in Mexico.

Urban developments in flood plains are historical in Mexico, the Tabasqueña Plain and the lower basin of Bravo River (Tamaulipas), Pánuco River (Tamaulipas and Veracruz), Coatzacoalcos River (Veracruz), Papaloapan River (Veracruz); the Coast of Chiapas, the Atoyac, Jamapa, Tecolutla, Nautla and Antigua Rivers (Veracruz) and Tulancingo River (Hidalgo) [1] are clear examples of areas where frequent flooding can be expected.

6. Additional contributing factors to flood events

In addition to the factors mentioned above, in Mexico, floods occur on low-lying areas of minor capital gain which are likely to be inhabited by the poorest sectors of the population. Also there exist a number of misperceptions, even of the authorities. For example, the idea that not using a territory during the dry season that is only flooded during the rainy season is a waste.

Furthermore, there is a land-use regulation by different laws and institutions from the three levels of government, which makes its implementation difficult, and a society with a low level of insurance culture, which leads the State becoming the insurer.

7. Cost of flood damage in Mexico

The cost of flood damage includes those associated with the impact on infrastructure at urban and rural areas; infrastructure for agricultural, industrial or commercial activities, as well as transport, communication and public services. This cost also includes indirect damages, which are those related to damaged or lost resources-dependent activities, for example, temporary or permanent job losses and stopping production chains.

Direct and indirect costs include tangible and intangible impacts, the latter are extremely difficult to assess and a common example is human health.

In Mexico, the National Center for Disaster Prevention (CENAPRED) collects information from the public and private sector and estimates the cost of damages due to natural and human-induced hazards, including those associated with hydrometeorological events.

In the period 2000–2015, damages from hydrometeorological phenomena have represented between 60 and 99% of total damages and losses at national level due to natural and socio-organizational events. Particularly noteworthy is the scale of the damages due to hydrometeorological phenomena in 2010, which amounts to approximately $4100 million, **Figure 5**.

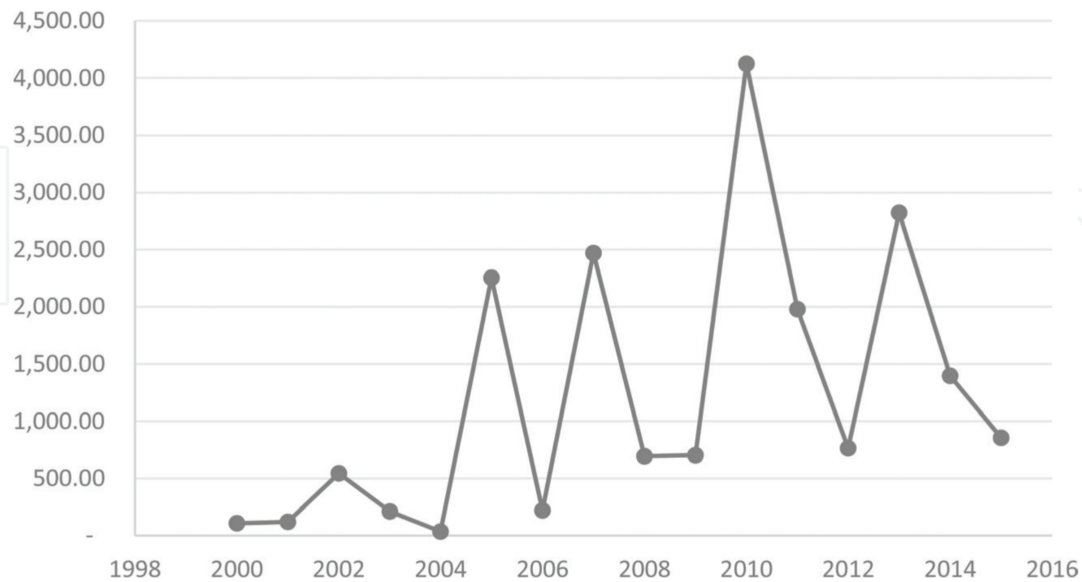

Figure 5. Cost of flood damage due to hydrometerological phenomena (mdd). Data Source: García et al., [7].

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8. Flood control infrastructure

In order to mitigate the risk of flooding in more than 639,000 km of rivers, a large number of flood control works have been built. In Mexico, there are more than 5000 km of compacted clay (in some cases sand) levees to protect population centres, industrial and agricultural areas against overflowing. When the flood plain conditions allows it, permanent diversion works are constructed, including relief channels for diverting excess flow into the sea, a lake or another stream. In places where there are large capacity channels for irrigation, they have been used for diverting [21].

In some cases when the neighbourhood of watercourses is lower, it is feasible to use them for flood retention even though this land is intended for livestock farming and agriculture; this option has been chosen as long as the damage is less than what would occur in protected regions. Another measure for flood control is to restore river conditions to recover the capacity of transport and suppressing of meanders [21].

River canalisation and piping of streams have caused problems in urban areas; however, in many instances, this kind of measures is necessary. Nevertheless, due to their size, dams offer greater protection; furthermore, they may have multiple purposes such as water diversion, water supply of urban areas, irrigation and power generation. It is worth mentioning that some are built for the sole purpose of flood protection. In Mexico, dams for flood and siltation control have been built to complement flood control actions. There are 810 large dams (classification of the International Commission of Large Dams); a total of 5700 have been inventoried and it has been estimated to be of the order of 8000 small dams and borders that remain unrecorded [4].

In Mexico, 54% of the dams are earth or rock fill dams, the second type in terms of the quantity is gravity section with 21%, followed by the buttresses representing only 5%, **Figure 6**. The highest dam is Chicoasén Dam, which belongs to the Grijalva Hydroelectric System with

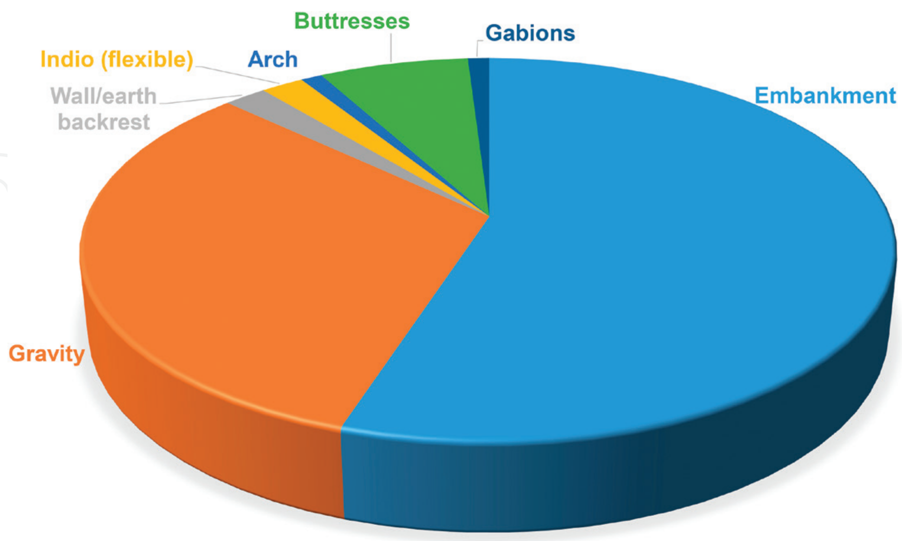

Figure 6. Types of dams in Mexico.

261 meters high, whereas the longest one is Falcon Dam, located between the U.S. state of Texas and the Mexican state of Tamaulipas, with 8014 meters length, although there are longer levees for flood protection in the city of Villahermosa, Tabasco.

9. Flood control actions

As previously outlined, since pre-Hispanic times Mexico has suffered from floods and has built infrastructure to deal with them; however, these solutions have generally been reactive and scattered actions. It is from the 1990s when comprehensive flood control programs have been defined such as those implemented in the state of Tabasco.

Later in 2014, the National Program against Hydraulic Contingencies was implemented, characterized by a preventive nature rather than reactive and promoting a coordinated participation of the governmental institutions responsible for flood management as well as the involvement of civil society.

The program is based on Integrated Flood Management and considers the hydrological basin and risk management, besides the adoption of the best possible combination of political, administrative, financial and physical strategies and a participatory approach.

A typical weak point in this type of programs is the uncertainty associated to the hydrometeorological information, and especially to climatic projections in Mexico, it is therefore required to:

- Prioritize the maintenance of hydrometeorological monitoring network.
- Have a national database of validated meteorological and hydrometric data.
- Generate scenarios and disseminate them in support of public awareness about flood hazard and risk.
- Develop the capacity of the institutions and implement technology focused on solving the national flood problem.
- Build resilience and sustainability in cities, both focused on delivering short-, medium- and long-term results, designing strategies and implementing actions to maintain essential activities and services during and immediately after a disaster without jeopardizing the availability of resources for future generations.

10. Use of technology in flood risk management

There are several institutions that have developed flood control technology, including IMTA, a decentralized public agency focused on solving national and regional problems associated with water resource management through research and technological developments.

Since 1986, IMTA has carried out projects in all the hydrological regions of Mexico, many of which are requested by one or more of the three levels of government and in other cases by non-governmental organizations, educational institutions or private companies.

Some of the projects developed by IMTA focused on flood risk management are as follows:

- Methodology for flood maps generation: a two-dimensional hydrological model, which allowed to visualize flow depth and velocity, was used to define levels of hazard, vulnerability and risk; it helped to optimize structural and non-structural measures as proposed.
- Flow characterization in urban areas: flood risk analysis in urban areas considered existing storm drainage infrastructure and runoff in streets by hydrologic and hydraulic modelling.
- Hydrological modelling: it was applied in hydrological forecasting systems for 24, 48 and 72 h that allowed to identify potential flood events and implementing timely measures to minimize damages and losses.
- Two-dimensional modelling using MDE (from LIDAR or Mexican Elevation Continuous Database CEM): IMTA has a collection of satellite and cartographic information from all over the country. Among its applications, there is a Flood Event Damage Estimation Module that assesses the damage for each MDE pixel.

11. Conclusions

Floods in Mexico lead to high losses due to the vulnerability and exposure of the population, rather than the extension of areas which are susceptible to flooding. Despite severe floods records in several regions of the country, their impact is communally underestimated.

Hydrometeorological monitoring and hydraulic modelling allow to predict the occurrence of floods and estimate the risk for a population centre and then design appropriate precautionary and control measures before the disaster occurs. However, particular attention should be given to the improvement of monitoring networks through maintenance, calibration and replacement, as well as the establishment of training and updating programs for stakeholders in flood management.

A global approach to water resources management should enable the identification of the causes, return period, extension of affected region and expected flood damage; the actual and potential effect of urbanization, as well as the planning, installation and implementation of structural and non-structural measures required for its control.

Among the non-structural measures is the implementation of a flood early warning system, the relocation of vulnerable and exposed buildings, the monitoring of changes in the watershed related to flood risk and the environmental effects of flood mitigation measures. Furthermore, inter-agency coordination is imperative to achieve adequate legislation.

The involvement of science, innovation and research in the design of flood control measures is essential to propose an effective combination of structural and non-structural measures; still the particular conditions of each case and weaknesses should be carefully considered, there is not yet an overall strategy.

The dissemination of flood risks and their impact, as well as the necessary actions for their management and positive Results, between civil society and authorities, is recommended.

One of the main reasons is the tendency to underestimate the magnitude of flood risk and not to consider it as a priority when it comes to allocation of resources.

Learning-based flood control and management measures designed to withstand flooding are part of building urban resilience, which is a necessity in the face of the unplanned urban growth proliferation, since this leads to an increase in social vulnerability, exposure and greater losses in case of disaster.

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