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Chapter

Flood Risk Assessment in Housing under an Urban Development Scheme Simulating Water Flow in Plains

Faustino de Luna Cruz, Oscar A. Fuentes Mariles, Judith Ramos Hernández and Jesús Gracia Sánchez

Abstract

Floods are increasingly occurring around the world more often, this implies analysing the risks connected to both human health and the environment, and to infrastructure and properties. The objective is to establish areas susceptible to flooding and their impact on the population through the effects on the unit of analysis "housing". To simulate the floods and map the affected areas, the FluBiDi 2D model was used. Two conditions for one urban zone analysed within the Mexico Valley were compared: (a) with the current hydraulic infrastructure and (b) with the application of rectification of channels. The available information was the discharge getting into the catchment and the total of homes in 2015. Projections for 20-year and 50-year planning horizon were considered, and for the 50 years, an evaluation of a non-structural measure was applied. Results show that under the current infrastructure, the flood simulated had a flow depth of 20 cm, decreasing to 5 cm average with rectification of channels, and a decrement of 45% of the cost of housing risk. Applying the both structural and non-structural measures, the cost of vulnerable housing was reduced until 94%, thus, this a trustworthy tool for decision-making in urban developments.

Keywords: flood risk prediction, FluBiDi, 2D-hydraulic modelling, flood management, hydraulic vulnerability, urban development

1. Introduction

Floods are increasingly occurring around the world, and for some authors such as [1–3], climate change is one of the most important causes for them since it affects directly and indirectly the river network. Although the contribution of climate change is undeniable, also there is the human contribution to increase the frequency of floods. According to [4], human contribution includes its settlement in risk flooded zones, and, as consequence, cities with highly developed infrastructure and commodities could generate instability in the fluvial system due to the implementation of morphological adjustments in order to protect agriculture or cities on or around the floodplain [5, 6]. The different flood levels of damage along the river are established according to the degree of the development of the region. A high-income region is more affected than a low-income region in terms of economic losses. However, low-income regions increase flood hazards since they have a poorly planned and managed infrastructure; thus, there is a growing population in a no suitable land such as floodplains and coastal and depressed inland areas, and economical losses are less than life losses [7]. When high- and low-income settlements are established in risk zones, some actions had been executed such as protective measurements as bank protection against migration, land protection constructing dam and levee systems and dredging [8]. However, these protective measures also have produced alterations in the channel and floodplain for a long time ago increasing the risk. Thus, it is necessary that flood control systems are matched with the river and floodplain changes and special care needs to be done to understand the causes and effects of the flood impact between natural and social environments in order to establish actions focused to minimise it [1, 7]. Ref. [9] considers that whether the purpose is the control of flood disasters, a flood risk management is clue, since it is the sum of actions to achieve the minimisation of the flood consequences. In general, [9] identifies two aspects that need to be addressed: the process of managing an existing flood risk and the planning of a system to reduce the flood risk. Generally, flood risk considered the probability of hazard (i.e. climatic change) and the exposure and vulnerability of the elements at risk (i.e. urbanised area) [1]. One way to predict flood hazards is as function of the computed probability of previous events known as return period (Tr). Flood hazards (exposure) represent *the exceedance probability of potentially damaging flood situations in a given area within a specified time period* [10]. In the case of vulnerability, it can be defined as *the potential for loss* [11], which could be associated in an urbanised system to the loss of the ecosystem services in the area. Although [12] pointed that urbanisation is not a synonym of an increment in flood vulnerability, some relationships could be expected. Urbanisation implies in some degree the presence of infrastructure, in particular against natural extreme events. An alternative is to consider both flood structural and nonstructural measurements as content.

In [13], the need for a quantitative but also a qualitative flood risk analysis was established. The first one provides information of the potential damage in terms of direct economic lost calculated using stage-damage functions (houses, industries and infrastructure), a situation that in the second case could not be achieved since it involves cultural, ecological and indirect economic damages [14]. One way to communicate both qualitative and quantitative hazard and the associated risk is through flood risk maps. For [15] there are flood hazard maps, which help to identify flooded areas with different probabilities, complemented by parameters indicating flood intensity, such as flood depth or flow velocity. Also, flood risk maps help to identify weak points of the flood defence system or indicate a need for action, even if the flood protection system adopted failure during the flood [9]. In fact, flood risk maps incorporate flood hazard information related to properties and population and their vulnerability to the hazard [1]. It is important to mention that many people have no other place to live, but they are habitual to frequent floods without representing any kind of lost. [16] pointed out that maybe due to the familiarity with flood or the lack of flooding experience, property owners in floodplains are not aware of the risk of living in a flood-prone area. The authors analysed the risk associated in terms of cost to protect their lives and properties. For that they mentioned that [17] were some of the first to manage the consumer perception of risk looking at the personal experience, history of past flooding, level of risk existing and how each individual responds to the risks. [16] stated that there is few information related to the effects of flooding risk on property values, the majority being focused to insurance by natural risk. They cited researches like [17–18] as the ones that use *property location vis-a-vis a floodplain* and the value of the property which reduces when it is in a flood-prone zone. However, in terms of economic aspects, it is only the responsibility of the house-owner and its perception of loss to have any insurance. This chapter looks at the property in terms of the economic loss as a function of the flood hazard zone location under three population growth rate scenarios at the north-east of the Valley of Mexico. The house prices were established according to the material used to build them and the impact when different flood intensity events (return periods) are applied. In order to achieve the flood risk map, a hazard map was created based on the identification of flood-prone areas and the impact in the implementation of a structural mitigation measure (hydraulic infrastructure) according to the hydrology, soil and climate, among other conditions of the study area. To identify the flood areas, the flood simulation was realised using the 2D mathematical model, FluBiDi (modelo de flujo didimencional), for different return periods previously calibrated using discharge data. The risk map contains the information about the consequences expected by the hazard (flood), specifically the influence of structural (channel rectification) and nonstructural mitigation measures (spatial econometric analysis of properties at risk).

2. FluBiDi mathematical model

In general terms, FluBiDi is a distributed 2D physical-based model for forecasting runoff developed by [19] and complemented by [20] the Institute of Engineering of National Autonomous University of Mexico (UNAM, in Spanish). Firstly, FluBiDi seeks to establish runoff for any site within a basin under study and determines the contribution volume of this site to the total basin runoff (including local rain). Secondly, FluBiDi provides an interpretation closer to reality since it incorporates several variables and parameters of the hydrologic cycle and basin characteristics based on the physical principles that scale changes are possible using parametric values [20]. As a 2D (dimensional) model, it represents floodplain flow as a two-dimensional field with the assumption that the third dimension (water depth) is shallow in comparison to the other two dimensions as [21, 22] noticed. FluBiDi, as most approaches solve the 2D shallow water equations, represents mass and momentum conservation in a plane and can be obtained by depth-averaging the Navier–Stokes equations. These equations are founded of the motion of viscous fluids involving parametrisation at a macroscale from the basic microscale equation in the vertical direction under the assumptions of hydrostatic pressure distribution and uniform velocity profiles. The development of the equations could be found at [23]. Thus, the momentum equations are.

$$\frac{1}{g}\frac{\partial u}{\partial t}+\frac{n^2|u|u}{h^{\frac{4}{3}}}=-\frac{\partial h}{\partial x}-\frac{\partial Z}{\partial x} \quad (1)$$

$$\frac{1}{g}\frac{\partial v}{\partial t}+\frac{n^2|v|v}{h^{4/3}}=-\frac{\partial h}{\partial y}-\frac{\partial Z}{\partial y} \quad (2)$$

where X and Y are forces by mass unit at the x and y directions ($m{\cdot}s^{-1}$); u and v are the flow velocities in x and y directions, respectively ($m{\cdot}s^{-2}$); and x and y are horizontal and vertical directions in the Cartesian system. The Manning-Strickler equation for friction slopes was included for computing roughness coefficient. Z is the surface water level related to the land topography considering the rain contribution and infiltration losses.

Also, the governing mass continuity equation considers the rain contribution and infiltration losses, and if the inertia is not significant, it is given as.

$$\frac{\partial h}{\partial t} + u\frac{\partial hu}{\partial x} + v\frac{\partial hv}{\partial y} = r - f \tag{3}$$

The diffusive wave approximation neglects the local acceleration term and convective acceleration term in the momentum equations, and it is applicable in situations where Froude number is small [24]. Thus, FluBiDi defines the system considering dynamic, diffusive and kinematic wave properties for an overland flow in a basin.

The integral form of the shallow water equations to define schemes on different mesh types is considered for the numerical integration; thus, a finite volume method needs to be used for the governing Equations [23]. The surface integrals represent the conversion of the lineal integral into area integrals implying to contemplate the boundary of the region that involves some integrations (Green's theorem). Some schemes consider the homogeneous conservative part of the system and a discretisation of the non-conservative term with a "lateralisation" [25]. For that, it is necessary to take into account that the mesh could have known depth and velocity values and the border boundaries consider four points: one for the right side of the intercell (R) and another for the left side (L) and the other two for above and below the cell.

FluBiDi is born as a hydraulic mathematical model to simulate runoff based on rainfall, and, in almost all the similar models, it considers river basins exposed to high rainfalls that present an organised drainage net, increasing the water flow at the mainstream according to the amount and intensity of precipitation and the topography at the basin [26]. However, in very few cases, this situation is presented, although it is the best condition to calibrate the model. Ref. [27] indicated that the river gauge water level time series comparison is one of the best forms to test the model's performance. For FluBiDi, a river basin in the Tabasco state offered input and output discharges measured and the awareness of how it behaves becoming an excellent option to calibrate the model. FluBiDi version 1.6 offered utilities to achieve hazard maps using routines to simulate the hydraulic phenomena obtaining water levels, velocities and water extension. Surface water levels could be used as a variable at the boundary conditions in FluBiDi. This is an important contribution, since very few codes have the ability to delimit boundary conditions and most of them require the definition of input discharge and water level.

3. Model calibration

Teapa River basin (TRB) together with Jalapa and Tacotalpa Rivers originate the La Sierra River with a basin (SRB) area of 1799.4 km^2. **Figure 1** shows the extension of the TRB. The TRB is an instrumented basin with hourly rainfall records, hourly water levels and flow gauging. Also, the TRB is subject to continuous historic floods being one of the most severe in 2007 with a Tr = 100 years. Particularly, at the Teapa station, the total drained area is 476 km^2, with records of average temperature of 25.9°C, with variations from 22.5° to 28.8°C during the year. The total annual average precipitation corresponds to 3133.4 mm, with average monthly variations of 105–520 mm [28, 29]. It is necessary to mention that the basin under study does not have any additional volume income to the precipitation; thus, the resulting flow corresponds only to the precipitation and the vegetation.

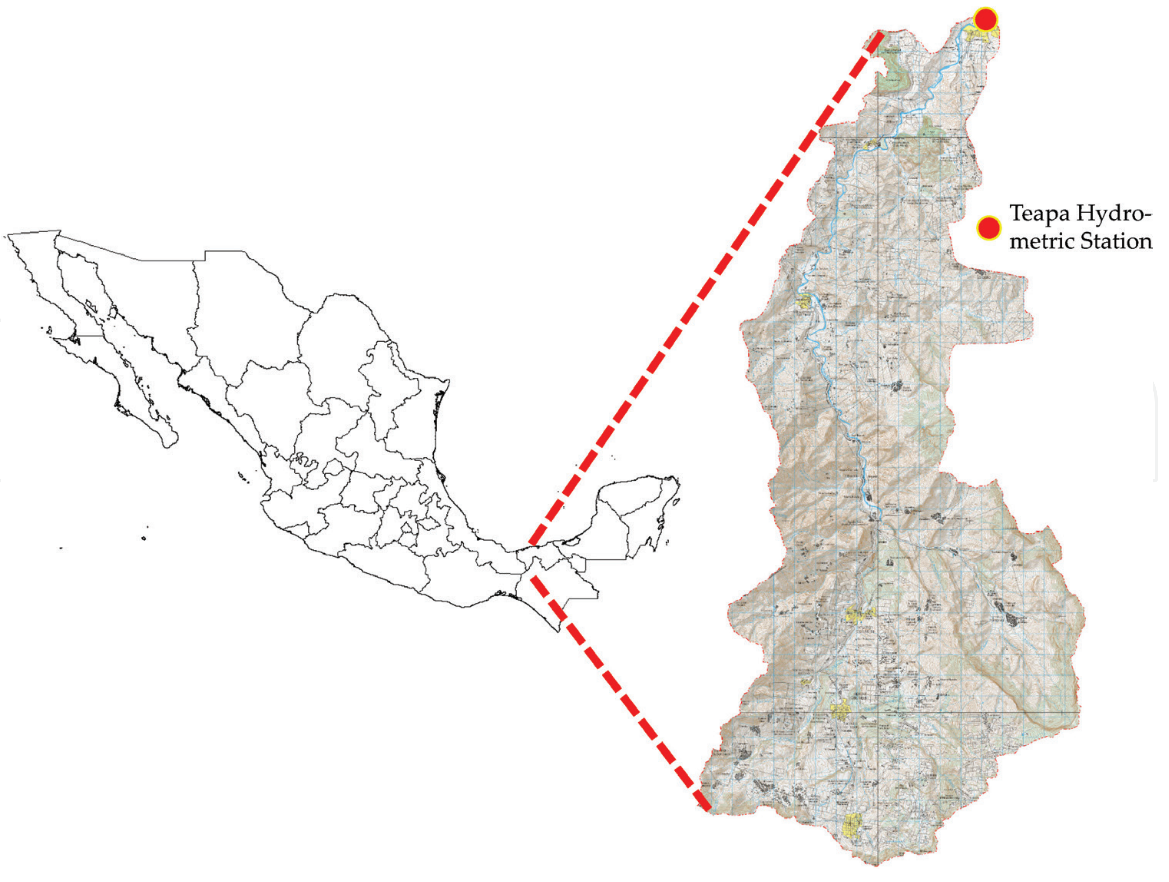


Figure 1.
Teapa River basin: Topographic relieve.

The natural vegetation consists of high evergreen forest and medium subperennifolia forest (limits with Chiapas) and grasslands and secondary subperennifolia secondary forest, with some popal [28].

3.1 Data

Many authors such as [27] identify as a common method to calibrate a flood model the use of historic flood records. In particular, if these records were acquired just after the event has passed, the accuracy of the model will be guaranteed. Thus, the main application of FluBiDi in TRB is the flood simulation by the estimation of the flow that drains at the outlet of the basin. To simulate flood, records include the period from November 19 to 24, 2015. In general, 2015 was classified around the country as the 12th year with more rainfall since 1941 with 872 mm of total cumulated rain. The reason for that was a series of cold fronts (CF) that hit the region in 2015 starting with the CF-7 (October 16–17) which left heavy punctual rains in Tabasco varying between 90 and 300 mm and generating in the SRB severe floods, the Teapa town being one of the places that remained uncommunicated with 1 m of water height. Then, the CF-8 (October 22–29) affected seriously the region by the day 25th with a cumulate precipitation of 160.7 mm, and this value increased with the arrival of the CF-14 (November 21–24) to 223.7 mm. In December 14–20, the CF-21 took place leaving rains around 125.4 mm in Macuspana by day 18th, but at the end of day 19th, rains were maintained around 120 mm in Puyacatengo. The heavy rains of the CF-21 caused that the La Sierra River to overflow and partially flood 13 communities, some of them, Teapa again, reaching in some cases a water height of 50 centimetres and affecting at least 350 families according to the Institute of Civil Protection of the Tabasco State [30]. There were also economic losses including flooded grasslands, and other losses were associated with low sales, absenteeism and delay of workers.

3.1.1 Meteorology and hydrometric stations

Meteorological data was obtained from nine weather stations located in the area (see **Figure 5**): Puyacatengo, Teapa, El Refugio, Francisco I. Madero, Chapultenango, Tapilula, El Escalón, Arroyo Grande and Oxolotan [31]. Data are provided in the latency of 10 min/hourly/daily rainfall (mm), 10 min/hourly and daily temperature (°C), hourly/daily relative humidity (%), average daily wind speed ($m{\cdot}s^{-1}$) and sunshine hours, among others. Also some daily evaporation records were obtained, but once they were compared with the effective precipitation, they have turned out to be negligible. These records could be used as an input to the model in order to simulate the event. In addition, the Teapa hydrometric station provides every 10 min continuous water level records obtained with an electronic system for real-time measurements and with quotation in the reference level bank of the hydrometric station. Daily water velocity using a hydraulic windlass method was acquired at 8 a.m. for each subsection in which the total section is divided using the divided channel method (DCM) [32].

It is important to know the spatial and temporal distribution of precipitation; thus, data for the nine weather stations were firstly grouped from 10 min to hourly rainfall values. **Figure 2** presents the analysis of spatial precipitation records for some hours, as well as the cumulative representation for the total modelling period of 6 days (144 hours).

The importance of the spatial-temporal analysis of precipitation can be observed since in the weather station (Chapultenango) rained the same or more that the cumulate rain for the total period of 7 days. In Chapultenango (see **Figure 4e, f**), the maximum rainfall value was around 250 mm for 1 h that corresponded to the maximum 24 h cumulative rainfall continuous value on November 23, whereas in the Teapa weather station, the maximum cumulated rainfall in 24 h was approximately 180 mm with less than 100 mm in 1 h.

Figure 3 shows the comparison of records for water surface level and water elevation discharge curves. **Figure 5a** presents the relationship between the real-time water level measurements and the daily gauge in the period under study; the error was less than 2%. **Figure 5b** indicates the water level related to the discharge is 330 times, which is used to carry out an adjustment to a quadratic polynomial function. This polynomial function provides the final discharge (Q) to the automatised water level measurements (without outliers present within the circle in **Figure 5b**). This provides from November 18 to 26, 2015, a total of 190 values of estimated discharges for 190 water surface elevations measured.

After reviewing the quality of rainfall information, it was considered that data ensure greater consistency to feed the mathematical model.

3.1.2 Topographic and thematic data

To apply the mathematical model, it is required to generate a mesh that represents the elevations and other topographic features (surface drainage system, slope and orientation) accurately. In this case, the digital elevation model (DEM) was obtained from the National Institute of Statistical and Geography (INEGI) Mexican Elevation Continuum [33]. Derived from the DEM (with a 30-m cell size), a mesh of 100 m per 100 m was resized in order to fulfil with the restriction for the modelled time required. Thus, for the new mesh, an interpolation technique was used where the main variable is the size against the calculation time. The merge of 100 m size is fed to the model in order to process it and recalculate variables such as slope, aspect, flow direction and basin limits.

A compendium of thematic maps, topography, climatology, edaphology, physiography, geology, hydrology, land use and vegetation, potential land use

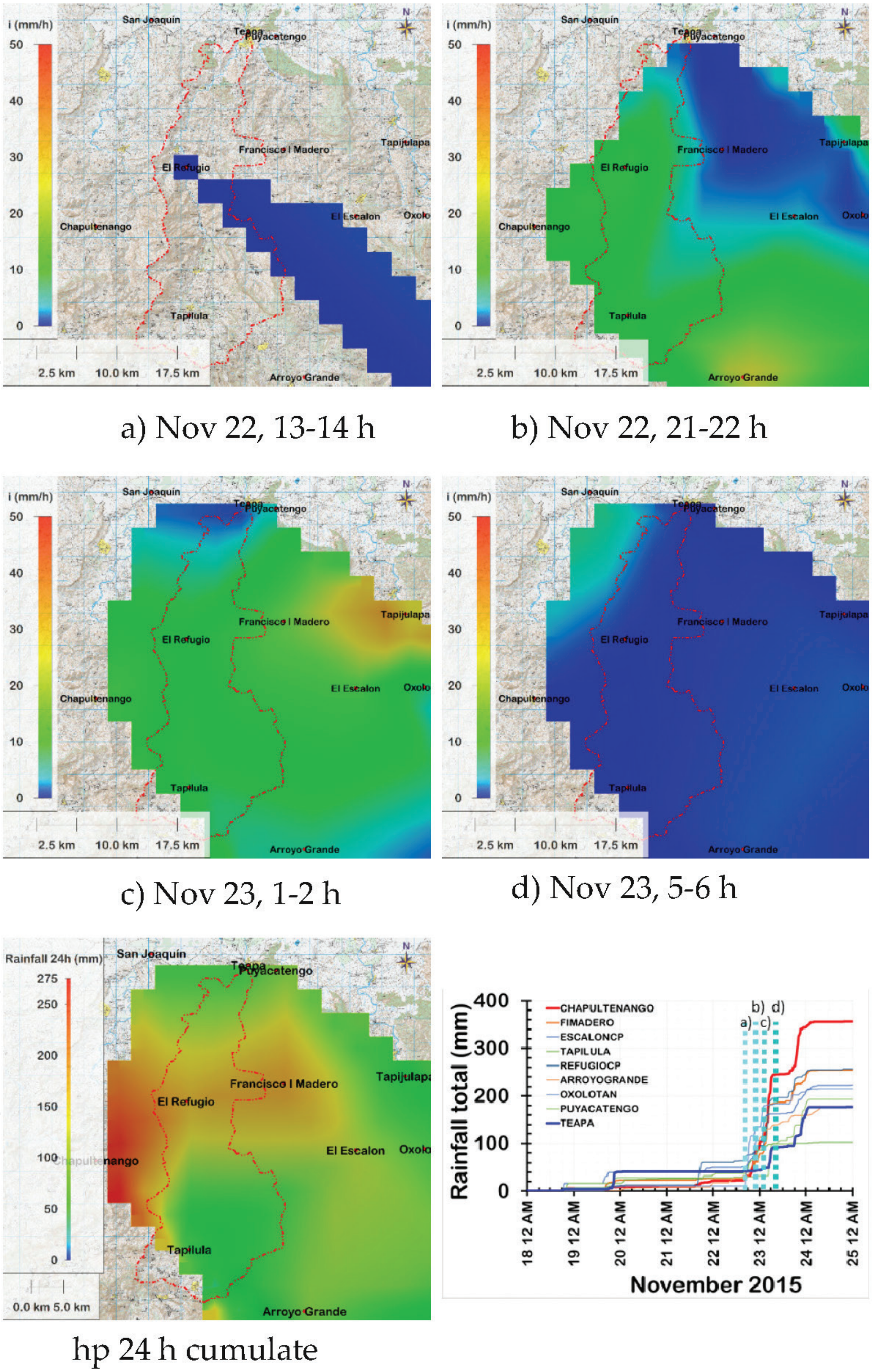
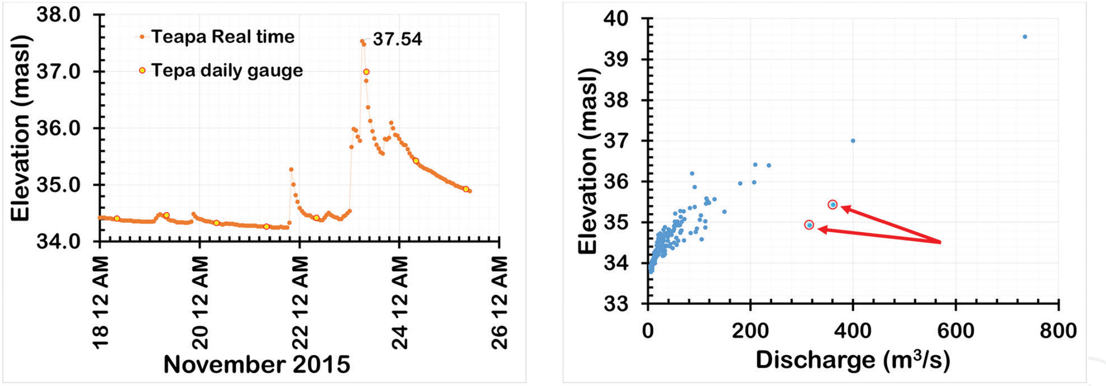


Figure 2.
Spatial analysis of precipitation from November 22 to 23, 2015.

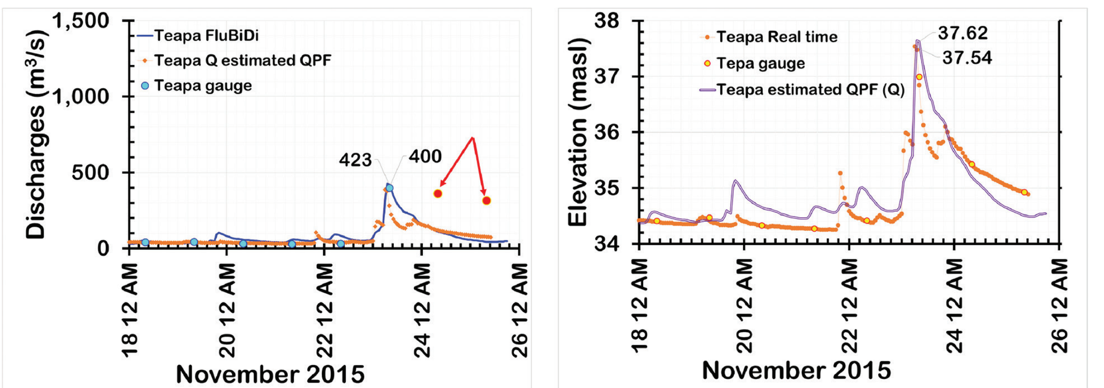
and communication channels, were obtained from [33]. These maps and other information available from documents were integrated in a geographic information system (GIS), according to its continuous or discrete nature. In the case



a) Water surface level

b) Elevation-Discharge Curves

Figure 3.
Water surface level and gauged records at the Teapa hydrometric station.



a) Discharges

b) Water depth

Figure 4.
FluBiDi results calibrated. Red points mean data measured are wrong.

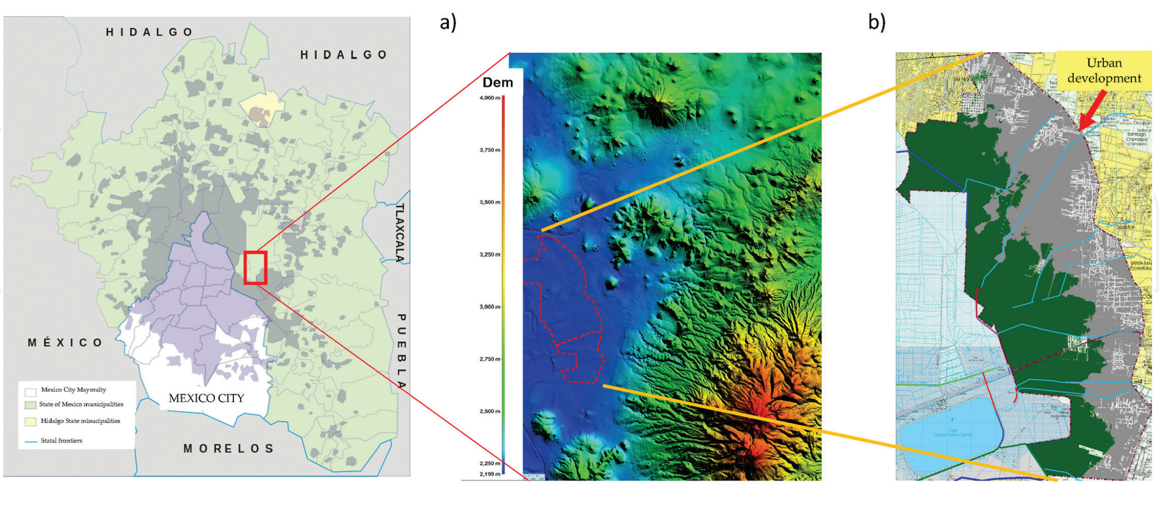


Figure 5.
Study area in the Texcoco ex-lake at the ZMCM.

of the land use map, it is very important for mathematical modelling since it is the base information for the mesh of the Manning roughness coefficient "n". It is necessary to mention that this coefficient can vary according to the time of the year; that is, for modelling in October–November, soil moisture increases to saturation; thus, the roughness coefficient also increases in a proportion of 0.03 and 0.05.

3.1.3 FluBiDi requirements

FluBiDi is configured to report flow depth and velocity data every hour, in order to compare results from the mathematical model with the correspondent real-time value measured at the hydrometric station. As response of the dynamic character of floods and the influence of water displacement downstream, FluBiDi provides flow equations in two horizontal dimensions, so water velocities correspond to its average value in vertical. For the simulation in the TRB, FluBiDi considers the contribution of water mass generated in the rainfall period that varies in time and space. Therefore, different hietograms are defined in different areas of the study domain. In the simulation of precipitation processes, it may be necessary to consider the infiltration of water in the no-saturate soil. Modelling infiltration is especially important to the transformation of rainfall into runoff. As it was mentioned, a mesh of the roughness coefficient of Manning “n” was obtained with the same resolution of grid from the DEM (100 m per 100 m side). The base flow was estimated in 40 $m^3 \cdot s^{-1}$ that corresponds to the one estimated directly from the reading of water levels related to the volumetric discharge.

3.2 Results

FluBiDi is a mathematical model created to be used in real basins that is the case of the TRB with a drained area of 476 km^2 and a volumetric flow rate of 400 $m^3 \cdot s^{-1}$ reporting data at each hour with an interval of 5 seconds for the calculation time step, estimating that 24 hours of rea.l time are mathematically processed in approximately 1 hour. In the model, it was the key to assess the maximum water level at the precise time when it is presented looking at the flood prevention. For this reason, in this calibration real precipitation data were used at the peak hours registered. Results are presented in **Figure 4** for November 24 at 6:00 am: an average volumetric discharge of 423 $m^3 \cdot s^{-1}$ was obtained using FluBiDi, and the value obtained from the hydrometric station was 400 $m^3 \cdot s^{-1}$; this implies a relative error (RE) of 5%. A median value of 34.766 in data measured and 34.764 in simulated was achieved, and a standard deviation of 0.64 and 0.66, respectively. The linear correlation is r = 0.87. The maximum water level has a difference around 8 cm of a total 4 m of water depth from 37.54masl head measured and 37.62masl head simulated.

In **Figure 6a** around November 24 and 25, there are two outliers that indicate the presence of a daily discharge relatively similar to the one observed on the 23rd. However, in **Figure 6b**, a water level increment similar to the one presented on November 23 was not reported. Therefore, as the volumetric rain coincides on the day of the maximum discharge and there are no other increases in subsequent water level days, it is considered that the gauge discharges may have an error in their methodology. If there is no rain, the discharge then maintains lower, and there is no transfer from another side because of the type of basin.

As shown, the model adequately predicts the discharge and water levels obtained from the precipitation recorded in the Teapa hydrometric station. This offers a very good agreement between FluBiDi and the measured values which guarantee an efficient rainfall-runoff relationship.

4. Application of model on an ungauged basin

Results from the calibration of FluBiDi were very satisfactory giving guarantee of the reliability of the model to be used with confidence in other basins with similar characteristics, even if it is ungauged at the output basin and without water depth references in the inundated zones. [27] mentioned three aspects that need to

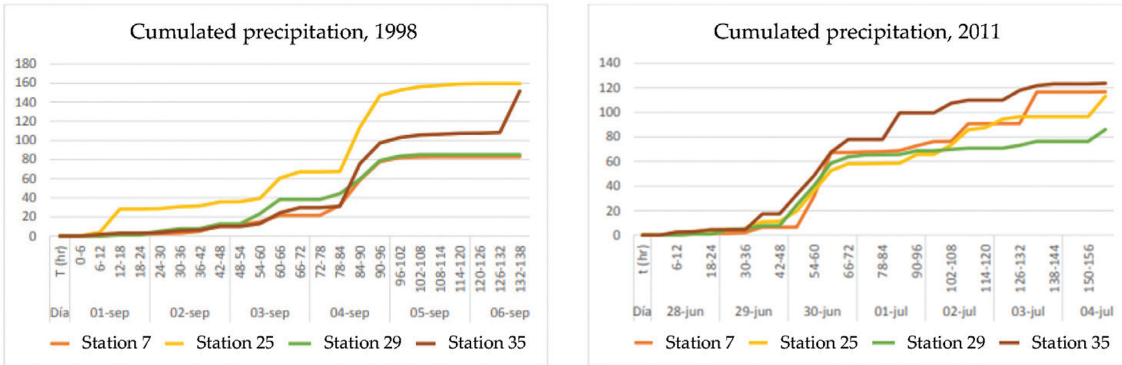


Figure 6.
Mass curves for station in 1988 and 2011. Source: [35].

be addressed by the model to simulate large events: *the interchange of flow between the channel and floodplain, floodplain storage capacity and flow resistance across the floodplain* due to soil and vegetation conditions.

4.1 Characteristics of the river basin

The study zone is located within the Valley of Mexico metropolitan area (zona metropolitana del Valle de México, ZMCM) at the west part corresponding to the Mexico State. The area involves the plain of the last ex-Lake of Texcoco, the largest one of an interconnected lake system during the prehispanic era. In **Figure 5**, the area of 92 km^2 can be shown with an average slope of 1% formed by an anthropic watershed defined by highways in the upper zone (the total contribution zone is 1020 km^2). The study area is located in the subbasin "p" of Lakes of Texcoco and Zumpango of the hydrological region Panuco No. 26, and it corresponds to an endorheic basin without exit to the sea. Thus, all the rainfall becomes runoff and generates the lakes.

The Valley of Mexico is surrounded by mountains on all four sides creating a basin with only one small opening at the north. There main types of climate in the study area are subhumid temperate and dry temperate and both semi-cold semi-dry with rain in summer. The dry season is subdivided into two: dry hot (between March and May), with predominance of dry tropical air and high temperature, and dry cold (from November to February) characterised by polar-type air with low moisture content and temperature. The region receives anticyclonic systems, producing weak winds [34]. The expansion of Mexico City implicated the drying of the lakes and the expansion of the urban sprawl towards the lowlands. Thus, floods are a constant problem with inundated plains and urban settlements in a constant flood risk. In 2015, there were approximately 60,000 homes susceptible to flooding; these homes are dispersed in the grey and green area (**Figure 5b**).

4.2 Data

In this case, the incoming flow to the system could be assigned to hydrograms coming from the upper part of the whole basin where some hydrometric stations are presented. The model was fed with eight hydrograms located each one in the river cut at the desire study area; they correspond to the vehicular bridges to cross the Texcoco-Tepepan highway over the riverbeds. Additionally, [35] provides local precipitation from four climatological stations (7, 25, 29 and 35) (**Figure 6**) located in the periphery but representative of the study area.

In 1988, there is a spatial difference in the rain observing between day 4 and 5 a cumulative rain of 24 h around of 90 mm in station 25, whereas in 2011 the spatial rain was almost homogeneous and of lower 24 h rain accumulating with 65 mm and with a mayor period of arriving. As result, it was determined that the rain is distributed in a homogeneous manner within the study basin, additionally to the size of the basin and the geomorphological characteristics. Therefore, a single station was proposed, which is the one that contributes with the hietogram fed to FluBiDi under a concentrated model of rain. Other consideration was to pose a hypothetical and very unfavourable event considering 5 consecutive rainy days. To this rain event, a statistical analysis was applied to four Tr = 20, 50, 100 and 200 years. Additionally, historical events were considered: Derby 1988 and Arlene 2011. Results are shown in **Figure 7**, a recurrence of less than 20 years for the 5 continuous days of rain, which is the case of interest in areas with little slope.

As well as in the TRB calibration (Section 3), thematic data was available as well as topography and land use since it is a swamp area with some human settlements, soil and vegetation which are easily determined, but the hydrogeological conditions become very complex. The topographic information consisted in LIDAR (light detection and ranging) scale 1:10,000 with a grid resolution of 5 m per size [33]. The mesh generated from it to feed the model was integrated by 1900 rows per 1020 columns to cover all the study zone with a resolution of 10 mX10 m in order to consider 1 sec as time interval to run the FluBiDi model.

Unlike the TRB, for this case there was no information that allows a quantitative calibration. However, a qualitative calibration was carried out based on historical information of the rainfall generated by the remnants of the hurricane Derby in September, 1988, and the TS Arlene on late June and early July 2011. Both remnants left prolonged rainfall over much south central Mexico wherein Mexico City is affected by subsequent flooding damaging hundreds of homes and several roads. This information was compared with flood maps from INEGI showing the areas that could be inundated for the study area [33]. Additionally, there was social information extracted from newspapers related to the water depth occurred.

4.3 FluBiDi application

The discharge from the eight streams coming from the upper part of the basin was represented with its correspondent histogram and feed to the model as initial condition. At this point, the structural measure was incorporated to the flood

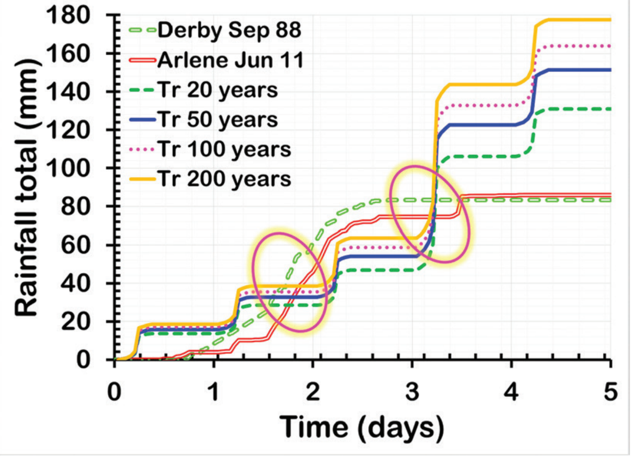


Figure 7.
Hp acumulada considerada en la modelación.

simulation process. This structural measure of mitigation is based on rectified and lining of the riverbed to have a perfect geometry. Thus, the flood simulation was done under two conditions (**Figure 8**): (a) with the current hydraulic infrastructure and (b) with the rectification of channels. Results were used to carry out the risk assessment under a scenario of urban growth in 20 and 50 years from 2015.

The FluBiDi model was run 10 times: 5 with current conditions and 5 with mitigation measure, from which the water depths and velocity values were obtained to (1) current conditions, (2) Tr = 20 years, (3) Tr = 50 years, (4) Tr = 100 years and (5) Tr = 200 years making each of the cells an area of interest and also to the historical condition for the remnants of the hurricanes Derby and Arlene. The urban growth is evaluated through the number of houses settled in the area; thus, in 2015 it was of 18,569, and its expected increment was favoured by the possible construction at the east of the new international airport of Mexico City. The number of houses expected to increase is of 52,800 in a 20-year planning horizon and up to 158,500 homes in 50 years.

4.4 Results

For each cell, it is possible to generate a limnigram as shown in the example of **Figure 9a** for a site in an area susceptible to flooding, but it is not the lowest, and some runoff is expected. **Figure 9b** shows the results of the model for the current infrastructure conditions, as well as the mitigation measures proposed for the four Tr analysed and the Arlene event in 2011.

Based on the hypothetical event and taking as reference Tr = 50 years, the maximum value under current conditions is 2232.1 masl passing with the mitigation measures at 2231.84 m. The major difference is that the inundated area takes at least 1 1/2 day to become flooded. Also, it is observed for Arlene that as a result of the mitigation work, the maximum flood levels decrease 28 cm (from 2232 to 2231.72) having the maximum value in 2 days later (from 2.3 to 4.3).

Due to the friendly output format from FluBiDi, results from the 10 mathematical simulations provided the envelope of maximum values of water depths for each cell and are presented in a map. Thus, one possible hazard scenario could be analysed throughout **Figure 10A** showing the current topographic conditions and **Figure 10B** considering the structural mitigation measure. Also, this kind of map was obtained for maximum velocities in each cell.

Comparing both maps, it was observed that the mitigation work effectively reduces those zones with higher elevations of water depth, although for lower elevation zones, water depths remain similar under both conditions. Channel rectification reduces that the river overspill; however, as this is a zone susceptible to inundation, it is impossible to eliminate the flood risk completely since there is the impact of the

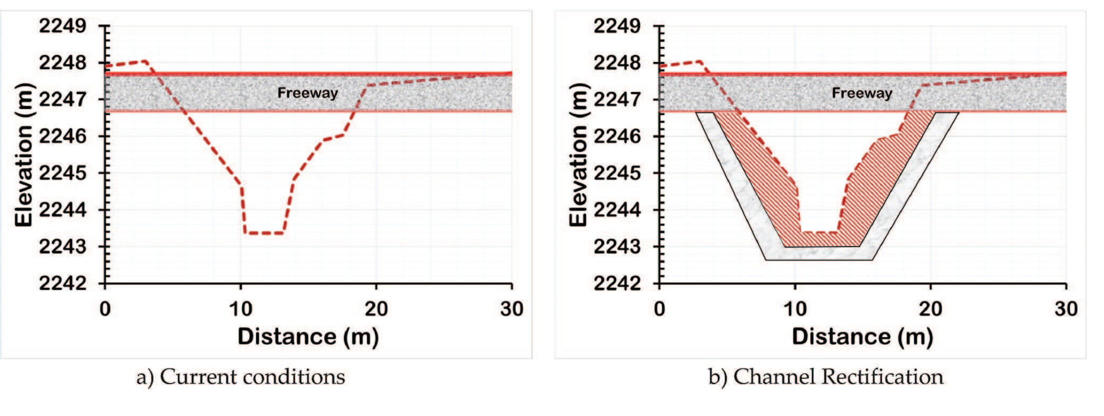


Figure 8.
Hydraulic infrastructure considered in the flood simulation using FluBiDi.

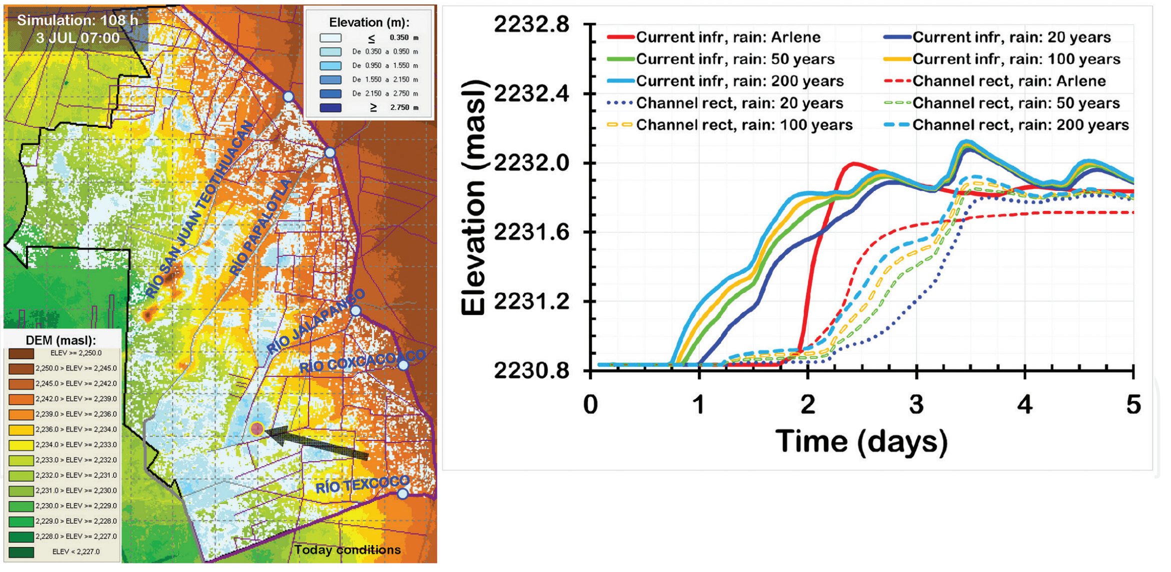


Figure 9.
Example of limnigrams for each cell.

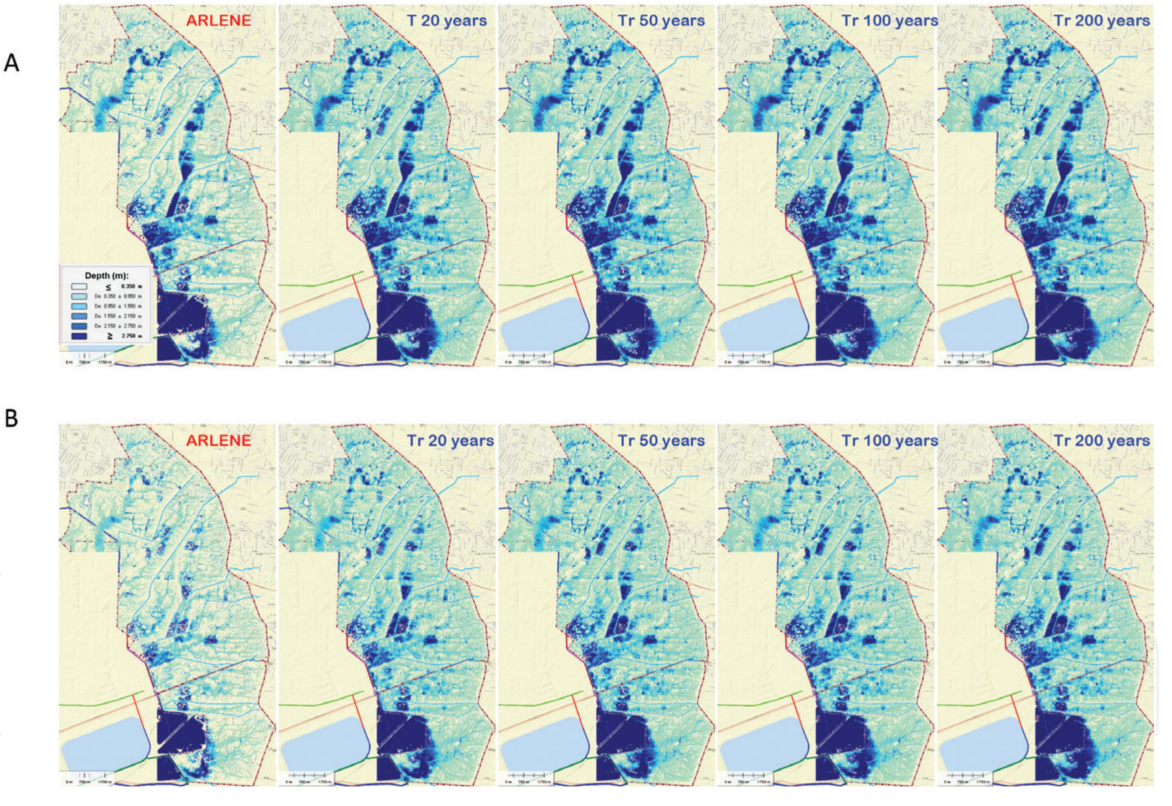


Figure 10.
Hazard flood maps considering as hydraulic infrastructure: (A) current conditions and (B) structural measure.

local rain. Thus, an important extension of the floodplain remains inundated although with a minor water depth as well as a small number of vulnerable houses; as long as people know there is an inundated zone, construction housing is limited. This situation leaves the necessity to improve water management in the study zone, and one option is to add a regulation associated to the amount of houses projected where the construction based on the hazard maps is allowed or not. In particular, for 50-year growth projection, the percentage of increment is 8.51 times the houses in 2015. Both measures, structural and nonstructural, were assessed in order to have a risk map. [7] mentioned that it is highly recommendable to use a nonstructural measure than a structural one. However, as it was observed here, the combination of both measures improves results reducing considerably the probability of flood. Also, as [7] indicated, one finds that a better understanding of the system is crucial, since as a susceptible area to floods, it cannot be ignored and expected that there is no any flood risk. On the contrary it will continue but at different degree.

5. Flood risk analysis

According to [36], maximum flood extent and water depth may be sufficient for hazard mapping and planning resources. However, velocity is essential in flood damage assessment; thus, in order to analyse the risk associated to flood events, a spatial economic analysis could be used since it considers the effects of floodplain hazard on property values (measure unit). In this case, the property values is related to the cost of the building that varies according to the socio-economic level of the people looking at the material cost and if the property is located within or without a flood-prone area. FluBiDi water depths and velocities were obtained for each instant calculation. Water depth was estimated for each cell of analysis considering an equidistance of 10 m; the guidance value corresponds to the maximum depth, since it is the one that causes the greatest damage in homes. Velocity was also available in each cell; being the premise that velocities are less than 0.5 $m \cdot s^{-1}$, this implies that there is no effect on the stability of the walls. Also, this means that floods in the area are slow and only walls and furniture in houses could be damaged. The criteria related to stability were confirmed using the Federal Emergency Management Agency Criterion, which provides a qualitative assessment of the stability of homes (with or without failure) which are located in the affected areas.

5.1 Dwellings

The INEGI (2016) has a national housing inventory that indicates the spatial location of dwellings and the main road access if it is available. For the study area, there are 23,826 houses according to the 2015 inventory. Also, the Prevention Disaster National Centre (CENAPRED) provides regulations typifying five classes of dwellings according to the building material of walls and to the furniture inside. For each class CENAPRED established a curve to indicate the dwelling vulnerability in terms of flood hazards such as the water depth. This vulnerability is presented as an index in order to provide a quantifiable damage in monetary units. In a market study carried out, three dwelling groups were identified focusing on the average real estate costs: 330, 240 and 190 thousand pesos. These groups correspond to CENAPRED's type II housing: one-level houses with walls and roof of constructed material and concrete floor.

One important point to be considered is that the study area is located in the vicinity of a possible focus of major urban development due to the construction of the Mexico City new international airport. The hypothesis considers that the new settlement of houses will be developed in the lower areas. Two scenarios were predicted: for an inter-media dwelling growth in 20 years, an increment of 52,800 houses is assumed, whereas for a scenario of maximum saturation (50 years), 158,500 houses are considered.

5.2 Dwelling vulnerability

Using the information obtained with the mathematical model for each cell and the maximum water depth, it is possible to associate the cell with the coordinate of the closest dwelling. This water level is the flood damage to the dwelling for each hydraulic infrastructure scenario at its respective Tr. **Table 1** presents the comparative summary for the 2015 houses and their degree of vulnerability under (a) channels at current conditions and (b) channels rectified.

Dwelling vulnerability comparison between current hydraulic conditions and rectified channels.

The rectification channels reduce the vulnerability at least in one-third, for the very high vulnerability and small differences were observed for very low vulnerability. For the other three categories, a proportional behaviour was observed reducing the number of housing as the degree of vulnerability increases. The same exercise was applied for the 20 and 50 years of urban growth projection. Also, the Arlene impact was analysed to the vulnerability being the one with less affectation to houses. Once the vulnerability index was estimated, the risk was computed based on the expected annual damage or "mathematical hope" of the occurrence of an event; this is represented by the area under the curve in **Figure 11**.

Results obtained indicate that for current houses, the risk decreases from 41 to 18 million $\$\cdot year^{-1}$, when the structural measure of channel rectification is implemented. For the 20-year projection of urban growth, the risk decreases from 280 to 102 M $\$\cdot year^{-1}$ when carrying out the rectification of channels. For the 50-years scenario (housing saturation) reduction was from 700 to 275 M$\$\cdot year^{-1}$ implementing the structural measure. These damage values are very useful for planning aspects in urban development, which can also be considered for insurance companies. **Figure 12** could be represented as maps as shown in **Figure 11**. For example, spatial dwelling at major or minor risk could be easily allocated in the map at the study area for the 50-year urban growth projection under the current hydraulic conditions.

As insurers consider the risk as the cost of the annual insurance premium, F represents a high number of homes but with a minor damage. Therefore, the value of the insurance in A is very high, and the owner will not opt for the policy. However, under present conditions there are few houses with gradeA, and they do not settle in low areas. Though, it is quite favourable that in a 50-year project, the tendency is to inhabit low-lying areas, increasing the risk of flooding and the value of the policy. Even in the urban settlement growth without and with rectification, the number of vulnerable houses decreases from 32,686 to 20,441, respectively. This would represent a decrease in the risk measured in the cost of housing of up to 60%. Also, for the urban growth of 50 years, when the nonstructural measure is added to the structural one, the reduction in the cost of vulnerable housing goes to 94%. Thus, the above provides a tool for decision-making in urban development without risk to the population. This confirm the [27] conclusion that to have a risk map is essential to define the possible impact in the floodplain location on property prices. Moreover, it is necessary to mention that the evaluation was carried out only considering the damage in housing; thus, the damage avoided is greater if one considers

Vulnerability	Dwelling vulnerability (houses)				
	Arlene (historical)	T 20 years	T 50 years	T 100 years	T 200 years
Extreme	252	618	692	755	805
High	235	304	365	403	421
Considerable	253	545	591	629	632
Moderate	481	922	1,025	1,077	1,124
Low	2,981	5,726	6,169	6,420	6,549
Vulnerability	Dwelling vulnerability (houses)				
	Arlene (historical)	Tr 20 years	Tr 50 years	Tr 100 years	Tr 200 years
Extreme	49	226	277	342	396
High	68	212	263	273	316
Considerable	150	400	468	539	592
Moderate	312	838	927	961	1,006
Low	2,542	5,421	5,843	6,134	6,407

Table 1.
Dwelling vulnerability comparison between current hydraulic conditions and rectified channels.

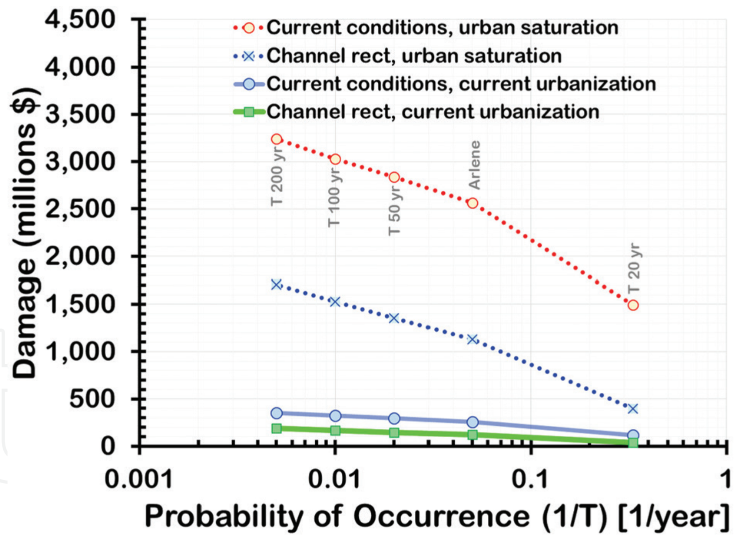


Figure 11.
Risk computation for each Tr and Arlene events considering 2015 conditions and at 50 years of growth with and without rectification.

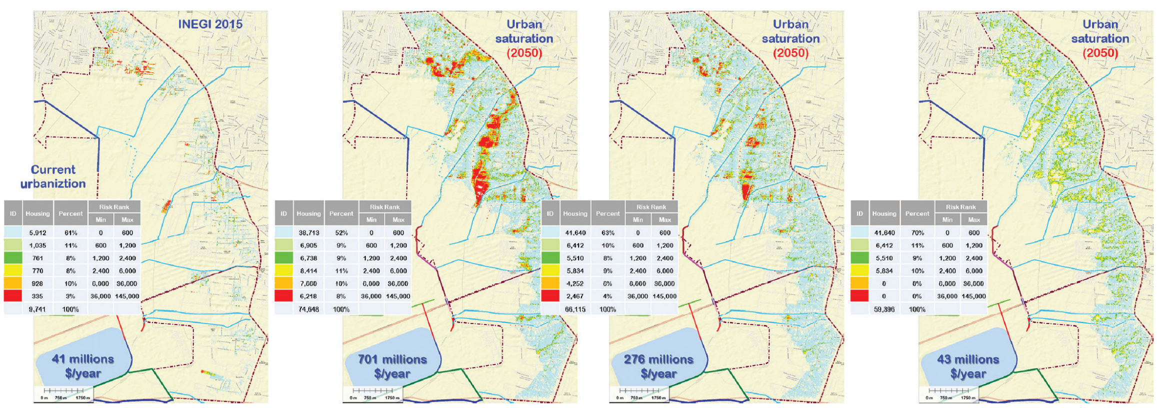


Figure 12.
Risk with current infrastructure (a), for 50 years of growth without rectification (b), for 50 years of growth with rectification (c) and with nonstructural measure (d).

other buildings such as schools, hospitals, roads, businesses and other aspects that affect economically the area.

In particular, for a 50 years of growth projection where the percentage of increment is 8.51 times the houses in 2015, both measures (structural and nonstructural) were assessed to have the risk map. This agrees with [7], in the high convenience to use a nonstructural measure, even more than a structural one. However, as it was observed here, the combination of both measures improves results reducing considerably the probability of flood. Also, [7] indicated one can find that a better understanding of the system is crucial, since as a susceptible area to floods, it cannot be ignored and expected that there is no flood risk. On the contrary, it will continue but at a different degree.

6. Conclusions

Floods are very dynamic affecting the river and its floodplain particularly during its displacement downstream. This makes FluBiDi a good option to simulate flood events using a real topography under different conditions such as gauged and ungauged basins. The model calibration is a crucial activity, for planning and public safety. The method used for FluBiDi calibration was ideal since there were data available constantly measured with different latency and accuracy. Results from the calibration were very satisfactory since discharge and water depth measured and simulated have less than 5% of error. This guarantees the reliability and robustness of FluBiDi.

Several tools were used (mathematical model, urban growth scenarios, hydraulic evaluation of mitigation measures, market studies of the type of housing) that together allow the planning of urban developments in flat areas that are associated with frequent floods. Flooding vulnerability in a basin with high developing urbanisation is potentially high when this urbanisation is located in flat areas, even if they are not subject to extreme climatic events. Achieving a harmony between society and the conditions of the ecosystem is relevant always recognising the interaction among exposure, sensitivity and adaptive capacity once flood vulnerability is analysed. This implies that it is possible that the development of the area is only a matter of living or using what one has. Thus, adaptation is possible in case of frequent floods, for example, to opt for the best type of house in order to reduce the risk such as stilt houses (raised on piles of wood or concrete), which are built primarily as a protection against flooding. These measures of adaptation, together with methods to control floods that happen in urban area, are ideal. These methods could consider different structural actions such as in this case it was the channel rectification as mitigation measure. However, also here it was demonstrated that effectively it is worth applying a structural measure, but in order to maximise results a nonstructural measure need to be applied reducing and, in some cases, removing the inundation risk. One important point to be considered is that the study area is located in the vicinity of a possible focus of major urban development due to the construction of the Mexico City new international airport. Planning, as a nonstructural measure, is perfectly a solution in urban growth development.

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