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DETERMINISTIC HYDROLOGICAL MODEL FOR FLOOD RISK ASSESSMENT OF MEXICO CITY

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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 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 (>0.75 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. In addition, three methods for flood map creation are proposed to assist flood risk management.

1. INTRODUCTION.

Every year, Mexico City is affected by severe flooding events, which are affecting deeply the urban environment and 20 million inhabitants. 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. [16]

According to Dominguez (2000), 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.

2. PROPOSED METHODOLOGY

2.1 Hydrological models.

In most of the cases, 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 able to simulate the runoff and propagation processes. In the case of the Mexico basin, the data are not available and the approach has to be reviewed by implementing an alternative concept. A potential alternative approach is to implement a deterministic distributed hydrological model. [11]

For the Mexico City Valley, the suggested methodology is based on the implementation of deterministic hydrological model with the Mike She modeling system [6]. MIKE SHE is an integrated fully distributed physically based hydrological modeling system developed by DHI [6]. It simulates water flow in the entire land based phase of the hydrological cycle from rainfall to river flow. The three models constructed are:

1. A basic hydrological model has been developed with a minimal data set. The model of the Mexico City catchment included a Digital Elevation Model (DEM) with a resolution of 5 meters 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.
2. A second model for the Hondo river sub-catchment in Mexico City with all of the above components and also distributed roughness values used for runoff according to vegetation types.
3. Finally, a third model for the Hondo river sub-catchment including all of the above components, plus the land use component and the unsaturated zone component.

The accuracy of the three is assessed by evaluation of the root mean squared error RMSE and of the Nash Sutcliffe coefficient E, calculated automatically by the software. The performance of the model is considered acceptable at $R^2 > 0.7$ and $RMSE > 2$.

2.2 Proposed methods for flood inundation and risk maps.

Three methods for the generation of flood maps are proposed:

1. Generate flood maps in ArcGIS using water level results from the hydrological MIKE SHE model simulation: The simulated water level can be applied in GIS to represent

flooding for several scenarios. The output of the hydrological simulation can be transferred to GIS in order to generate flood layers for different scenarios.

2. Generate flood maps applying the simulated discharge from MIKE SHE in a MIKE 21 model: The main elements to construct a MIKE 21 model are: Model topography, closed boundaries along the edge, location and magnitudes of the inflow and outflow boundaries, and the hydro-dynamic parameters. [9]
3. Generate flood maps in MIKE SHE: This method uses the two-dimensional diffusive wave module of MIKE SHE, which can simulate friction dominated flow. Model geometry is input using terrain raster, and 1-D MIKE 11 channels are incorporated.

3. APPLICATION TO MEXICO CITY BASIN.

3.1 Description of catchment

The study area has a size of 2800 km². The rivers modeled in are the San Javier, Tlalnepantla, Hondo, Tacubaya, Mixcoac, Piedad and Magdalena, and the Great Channel, the National canal, and the Remedios channel as well. Figure 1 shows the Mexico City catchment, and the hydro meteorological network.

Figure 1: The Mexico City catchment and the hydro meteorological network.

3.2 Available data.

The following data are available: a DEM with 5 meters resolution provided by the Institute of Statistics and Geography; the river and drainage network as shape files; cross sections extracted from the DEM within the GIS software; daily rainfall values for 44 stations and their location, daily evaporation values for 5 gauging stations (Aguiles Serdan, Molinito, Magdalena, San Bartolome, Huixquilucan); land use shapefiles for agriculture; forests, grassland and urban area,; shape files for seven types of soils; observed average daily discharge for the 11 hydrometric stations (San Bartolo, Molinito, Molino blanco, Conde, San Juan, Santa Teresa, Arboledas, Etchegaray, Puente de Vigas, Calacoaya, Gran canal); and Strickler roughness coefficients associated to different vegetation covers.

3.3 Development of the models.

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

- Model domain: According to the Water Commission of Mexico (CONAGUA), there are 730 hydrologic catchments in Mexico. The analysis is focused on the catchment RH26 dp.
- Topography: A 90 meters resolution DEM associated with a projection in UTM zone 14N.
- 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.
- River network: The hydrographic river network consists of a linear shape file system.
- Cross sections: The cross sections were evaluated using the River Bathymetry Toolkit.
- Daily average observed discharge data were obtained for 11 stations for the year of 1981.
- A uniform Strickler roughness value of 20 was used for the overland component of MIKE SHE, and a uniform value of 30 for all river beds.

The second model covering the Hondo sub-catchment included a river network, rainfall, topography, and distribution of the Strickler number based on vegetation data. Figure 2 shows the location of the Hondo sub-catchment in the catchment of Mexico City and the hydro meteorological network. The model area is 173 km².

Figure 2: Location of Hondo sub-catchment in the Mexico City catchment & River Hondo sub-catchment with hydro meteorological monitoring network.

The overall distribution of Strickler coefficients is presented on the figure 3. The rainfall distribution is shown on figure 4. The model was simulated for the same period as model 1.

Figure 3. Strickler coefficient distribution.

Figure 4. Rainfall distribution.

For the third model covering the Hondo catchment, the unsaturated zone (UZ), evaporation and land use components of MIKE SHE were applied. The rainfall distribution for model 3 is the same as in model 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. For all models, a period of 1 year was chosen (1981) when data were available for all rainfall and gauging stations. The simulation time step was 10 seconds in MIKE 11 (hydraulic component of Mike She).

4. RESULTS.

Model 1: Figure 5 and figure 6 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 values for St. Teresa and Molino Blanco stations are 2 and 3.34 respectively. The E values obtained are -0.03 and 0.73 for the same stations.

Figure 5: Molino Blanco station simulated discharge against observed discharge for the Mexico City catchment model.

Figure 6: St. Teresa station simulated discharge against observed discharge for the Mexico City catchment model

Model 2: For the model of the Hondo river sub-catchment, the Strickler coefficients have been distributed over the basin according to the vegetation types. The resulting hydrograph can be seen in figure 7. The model produced a value of 0.71 for the E coefficient and 3.48 for the RMSE coefficient.

Figure 7: Molino Blanco simulated discharge against observed discharge Hondo sub-catchment model including the effects of vegetation in Strickler coefficient.

Model 3: The third model for the river Hondo sub-catchment includes the land use component and the unsaturated zone component. Results for the coefficients were obtained of $RMSE = 3.05$ and $E = 0.77$. Figure 8 represents simulated discharges in Molino Blanco gauging station compared to observed values.

Figure 8: Molino Blanco station simulated discharge against observed discharge in Hondo River catchment model with unsaturated zone and land use components.

5. CONCLUSIONS.

The statistical coefficient values in Molino Blanco station for the three models are listed in table 1. As the St. Teresa station was not assessed in models 2 and 3, its results are not included in this table.

Table 1. Statistical coefficients of the three models of study.

	Molino Blanco	
Model 1	RMSE	3.34
	E	0.73
Model 2	RMSE	3.48
	E	0.71
Model 3	RMSE	3.05
	E	0.77

Model 1 has 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. If the cause for this loss of stability could be found and fixed, the result would improve considerably for this model.

Model 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. This could be caused by errors when implementing the Strickler coefficients related to vegetation cover.

Model 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. Nevertheless, model 3 provided the best result and it is recommended for hydrological studies of the Mexico City catchment and its sub-catchments; at least until the issues associated to models 1 and 2 can be resolved.

6. FUTURE WORK.

As the significance of the MIKE SHE deterministic hydrological model has been confirmed by this study, it is recommended to apply the results from the simulations to generate flood maps. Three methods for flood inundation maps are described in the methodology and will serve to carry out a first flood risk assessment in the Mexico City catchment.

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