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Assessing Flood Severity and Risk to Residents in Bosque Chapultepec

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Abstract: *This paper aims to study storm events that lead to urban flooding and their after-effects in Bosque Chapultepec, an urban forest located in Mexico City. Considering Bosque Chapultepec's landscape configuration and composition, along with micro-watersheds that drain into the four-sectioned study area, the water depths and velocities were estimated through hydrodynamic models in Iber derived from design storms for different return periods between 2 and 10,000 years. Risk to human safety assessment due to flooding was determined in terms of flow depth and velocity using the Dorrigo classification; and vulnerable zones prone to endanger people to be dragged by the flow were determined and classified following approach proposed by Milanesi, Pilotti, and Ranzi which has an inherent relationship not only to topographic data – since is one of the main data input in hydrodynamic simulations to create flood depth and velocity rasters – but also to human body conceptual model of human stability in a flow. 100-year return period storm events showed that more than 60% of area affected by flooding would not cause damages to light structures, vehicle instability nor reduce people's ability for wading; and more than 90% on area where people were at risk of being washed away corresponded to very low levels, meaning that people passing by the forest only need to be cautious. Furthermore, in light of the latter, recommendations were proposed to prevent flooding in Bosque Chapultepec and to reduce both flood severity and risk to residents to being washed away.*

Keywords: *Bosque Chapultepec, Mexico City, flooding, risk, Dorrigo, Milanesi, Iber*

1. Introduction

Hydrodynamic processes occurring within the hydrological cycle are inherently intricate and marked by considerable uncertainty, lacking a singular theory that comprehensively integrates all aspects of hydrology and hydraulics. Nonetheless, in recent decades, computer programs development has facilitated the generation of simulations using numerical models. These simulations serve not only to estimate water availability within a given region but also to emulate its behaviour—whether above or underground—including factors such as flow, velocity, depth, and disturbed extension. Primary objective is to facilitate preventive measures or problem-solving assessments, addressing various issues, including social concerns.

Regarding damages inflicted by water excess in Mexico over the past three decades, approximately 67% of natural disaster-related deaths are attributable to storms and floods. These events have been responsible for up to 40% of the national disaster damage recorded at 2018 year. [1, 2].

Additionally, in Mexico, the National Centre for Disaster Prevention (CENAPRED, by its acronym in Spanish) monitors and evaluates flood hazard, its incidence through the quantification and parameterization of the factors involved in it for it then to be expressed as a hazard [3]. Some of these parameters are water depth and velocity, toppling or slipping [3], which for hydro meteorological effects phenomena studies done in Mexico are applied in following criteria:

The Federal Emergency Management Agency (FEMA) and the Federal Office of the Economy of Water (OFEE, by its acronym in French) link the maximum water depth and velocity values to be expected and thus characterise the flood into three hazard categories (low, medium, and high) to describe whether buildings will be affected or if people are vulnerable both outside and inside these structures. Nanía and Témez's criteria characterises flooding as dangerous or non-dangerous based on the impact that water depth and velocity has on human stability to slipping [3]. The Mexican Institute of Water Technology (IMTA, by its acronym in Spanish) characterises risk of flooding by classifying it in four hazard levels, also due to toppling and slipping, as well as

characterises the risk associated to affectations to family homes and the loss of property within them [3, 4]. On the other hand, method used in Dorrigo, Australia, defines five flood severity levels (from very low to very high) based on an expected maximum water depth and velocity value, in which it is evaluated vehicle instability, adult people's ability for wading as well as possible structural damage of light structures [3, 5].
In this paper, it is determined water amount entering to the Bosque Chapultepec's land by rainfall for different design storms, focussing the analysis not only on the behaviour of the surface runoff but on the events that cause flooding as well. In this analysis, Dorrigo approach [6] is applied to determine flood severity; level and methodology proposed by Milanesi, Pilotti & Ranzi [7] is also applied to define areas where people are in risk of being dragged and classify its vulnerability level. Latter method is based on the assessment of the destabilising effect of local slope on a regional population to slipping and toppling. Required data on inflow, water depths and velocities for both methodologies are estimated using the software Iber [8], ArcGIS [9], and HEC-HMS [10].
The use of these two methodologies further allows appreciating measures for safeguarding citizens within the Bosque Chapultepec and surrounding areas, reducing runoff that could generate damages, and for water usage resources.

2. Materials and methods

2.1 Study area

This paper presents a study focused on Bosque Chapultepec, which is categorised as an urban forest, and is broken down into three sections that are located in Miguel Hidalgo borough, in Mexico City, Mexico; to which Military Base 1-F is also annexed as fourth section in Álvaro Obregón borough a field that belongs to the Ministry of National Defence (SEDENA, by its acronym in Spanish). Bosque Chapultepec is geographically located between parallels 19°23'40" and 19°25'45" N, and between meridians 99°10'40" and 99°14'15" W, at an altitude between 2250 and 2340 masl, in foothills of Sierra de Las Cruces' volcanic mountain.

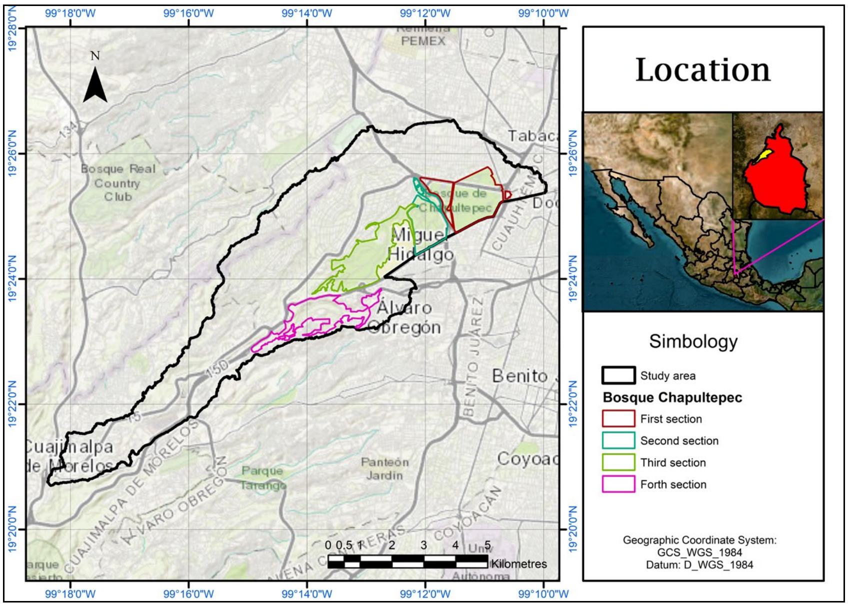

Fig. 1. Study area

Currently, a total 274,086 hectares area is covered by First Section, 168,032 hectares by Second Section 168,032 hectares, and 243,904 hectares by Third Section, while Fourth Section spans a 152,214 hectares area. Within study area, micro-watersheds contributing runoff to urban forest are also considered, resulting in a total area of study of 4420,697 hectares (Figure 1). This entire area is located between parallels 19°20'42" and 19°26'32" N, and between meridians 99°9'57" and 99°18'23" W, at an altitude between 2250 and 2225 masl, according to LIDAR terrain model, with a 5 x 5 metres horizontal resolution [11].

2.2 Physio-hydrological characterisation

Major soil types in study area are Feozem Luvic and Petrocalcium [12]. It was resumed at digital land and vegetation use representation created by IMTA, 2022, based on satellite images and aerial photographs, which considers several classifications such as forest, street, canal, stream, water body, residential, scrubland, grassland, dam, bare land and urban built; residential, street, and urban built land use cover study area 74.95%, followed by forest that covers 11.41%.

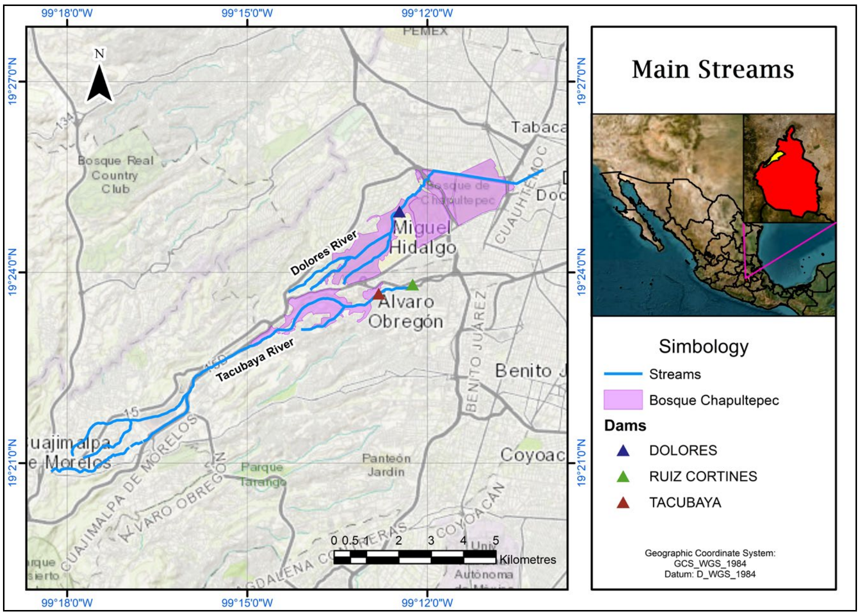

Fig. 2. Main streams located in the study area. (Source: [13, 14])

Within study area, two main intermittent streams are located: Tacubaya and Dolores. Likewise, there are two dams for flood control, each one situated on two aforementioned streams: Dolores and Tacubaya (Figure 2). Other water bodies additionally located in Bosque Chapultepec are artificial lakes Mayor and Menor (excavated in the late 19th century), which are divided between first and second sections of the urban forest. Next meteorological and hydrological studies were obtained from the General Report, first stage, carried out by IMTA [15]: " DIAGNÓSTICO Y PROPUESTAS PARA LA GESTIÓN DE LOS RECURSOS HÍDRICOS EN LAS CUATRO SECCIONES DEL BOSQUE DE CHAPULTEPEC " and are described below.

2.3 Meteorological study

In Table 1, it is shown the maximum precipitation depth in 24 hours for selected return periods from 2 to 10,000 years, which was obtained by calculating the influence area using Thiessen polygon method, for maximum precipitation values estimated from Double Gumbel Probability Distribution Function for each climatological station.

Table 1: Maximum precipitation depth in 24 hours for different return periods.

T	hp	T	hp
years	*mm*	*years*	*mm*
2	42.645	200	91.321
5	58.320	500	96.072
10	67.687	1000	99.240
20	74.924	2000	102.117
50	82.443	5000	105.547
100	87.183	10000	107.896

Figure 3 shows a unit hyetograph in orange that corresponds to mean value of all the storms analysed from the Synoptic Weather Station Tacubaya, while it also shows a unit hyetograph in blue that represents the mean value of the storms that reached 80% of the precipitation before 10 a.m. Since the latter hyetograph represents the worst-case scenario, it was used to define the 24-hour temporal distribution of the design storms, for each return period, in the hydrologic model and the two-dimensional hydraulic model.

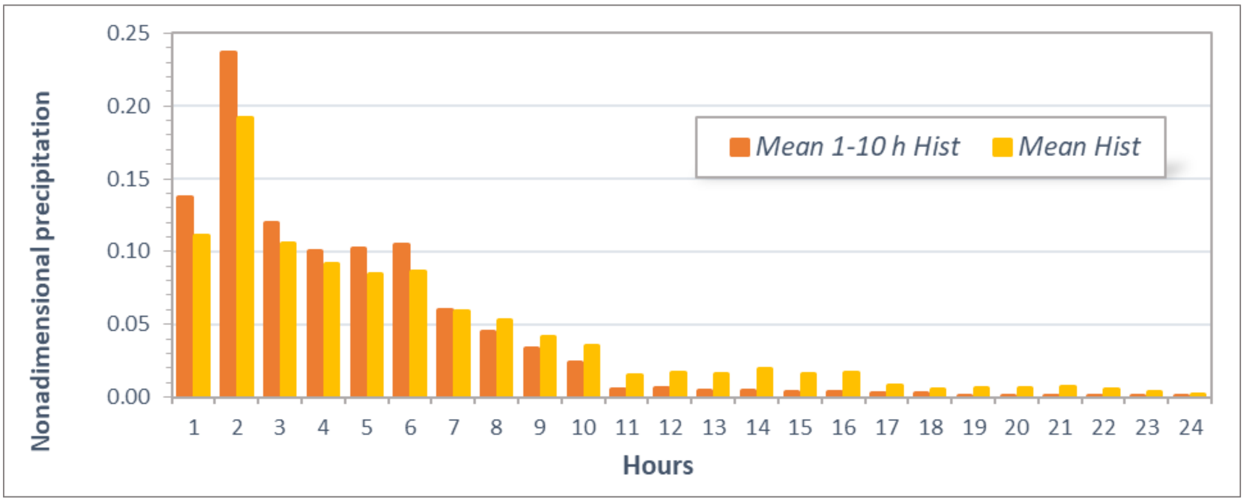

Fig. 3. Unit hyetograph. (Source: [15])

2.4 Hydrological study

Table 2: Micro-watersheds characterisation that comprises study area.

Micro-watershed	Area	Length of main channel	Elevation difference	S (Channel slope)	CN	Tc	tr
	km²	*km*	*m*			*hours*	*hours*
Dolores	4.14	4.21	165.47	0.01525	82.73	1.06	0.63
Tacubaya	9.66	12.45	492.5	0.01631	88.08	1.64	0.99

Main physiographic micro-basins characteristics contributing runoff into Bosque Chapultepec, Dolores and Tacubaya, are shown in Table 2: main channels slope was computed by Taylor Schwarz's method, curve number CN, the mean Tc value estimated by Kirpich, Rowe, SCS and Chow's methods; and the tr computed with Chow's equation. This information was introduced into the software HEC-HMS 4.2.1 for hydrological modelling; the following results were obtained:

Table 3: Runoff computed in HEC-HMS of contributing micro-basins.

Micro-basin	Peak discharge, in m^3/s, for each return period (*years*)											
	2	5	10	20	50	100	200	500	1000	2000	5000	10000
Dolores	2.5	4.5	5.8	6.8	7.9	8.5	9.3	9.8	10.3	10.7	11.2	11.5
Tacubaya	5.1	8.5	10.5	12.1	13.8	14.9	16	16.8	17.6	18.2	19	19.5

2.5 Two-dimensional modelling in Iber

To carry out hydraulic simulations using Iber, the study area was divided into four models that contain the following sections of Bosque Chapultepec in the next order: the first and second sections, the third section, the fourth section, and the upper Tacubaya basin; in order to optimise the simulation processing since it was necessary to represent the hydraulic infrastructure in greater detail, and it was not possible to model the five areas as a whole. The geometry of each model included:

a. Boundary conditions and outlet boundaries: The boundary condition was assigned as an output with a supercritical/critical regime for the main boundary of each model. For the model containing the first and second sections of the urban forest, an inlet boundary was assigned as an upstream boundary condition to the entrance of the Dolores dam where it was introduced hydrographs obtained from simulation of the forest's third section modelling for each return period, with a critical/subcritical regime, as the total inflow in the inlet. For the model of the fourth section of the forest, an inlet was assigned as a boundary condition in the upper area introducing the hydrographs obtained from previous simulation of Tacubaya micro-basin, assigned as total inflow for each return period, with a critical/subcritical regime.
b. Initial conditions: non-existent flow condition (without previous rainfall) was established as a water depth equal to zero in the entire area to be modelled except in the four artificial lakes to which a depth of 0.3 meters was assigned.
c. Design Storm Hyetograph: Total rainfall input to model by return period from meteorological study.
d. Roughness coefficient: Manning's coefficient was assigned based on land use map created by IMTA [15] and based on values suggested by Ven Te Chow [16], combined as well with values specified by default in the software Iber.
e. Infrastructure: Circular and rectangular culverts were put where bridges crossing channels were detected, with a Manning roughness coefficient of 0.02. Sinks were added to represent the storm drains connected to the storm sewer of Mexico City.
f. Generation of unstructured triangled meshes, entering element sizes of 2, 4, 5 and 6 meters.
g. Digital elevation model: To set elevation on unstructured meshes, DEM generated from a 5-meter LIDAR was used, merged with a 1-meter LIDAR DEM just in certain places where the Mayor and Menor artificial lakes are located.

In total, 36 hydraulic models were generated which correspond to four sections and twelve return periods.

2.6 Flood severity, applying Dorrigo approach

To estimate flood severity level or flood hazard in buildings after storm events, the National Water Commission (CONAGUA, by its acronym in Spanish) for the National Program Against Hydraulic Contingencies (PRONACCH, by its acronym in Spanish) used Dorrigo criterion [6] by adapting its Flood Hazard Diagram, which also making hazard maps associated to flood events for a particular study region (Figure 4). Only water depth and velocity rasters obtained from *Iber* simulation were used as inputs, each one extracted per hour as time step for return periods of 2 to 10 000 years; and that were processed through the ArcGIS tool Model Builder. Flood severity index classified for map generation are described in Table 4, where green represents areas with no critical damage while red represents areas with potential severe or critical damage.

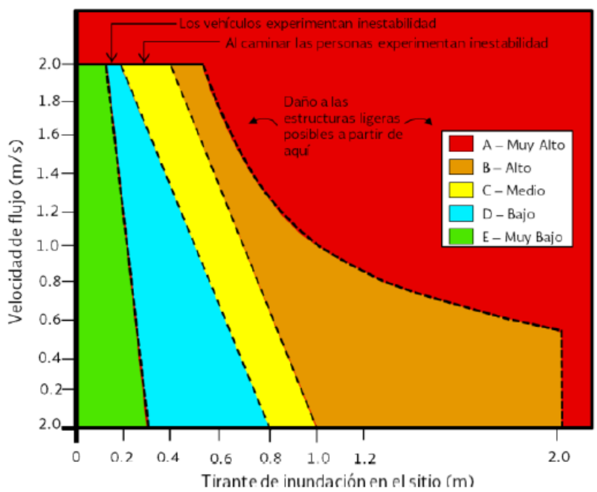

Fig. 4. Flood severity indexes according to the Dorrigo approach. (Source: [6, 17])

Table 4: Colour coding for creating flood severity maps.

N°	Letter	Index	Colour	Constraints	
				Depth (*m*)	Velocity (*m/s*)
5	A	Very high		Y > 2	V > 2
4	B	High		1 < Y ≤ 2	V ≤ 2
3	C	Medium		0.8 < Y ≤ 1	V ≤ 2
2	D	Low		0.3 < Y ≤ 0.8	V ≤ 2
1	E	Very low		Y ≤ 0.3	V ≤ 2

2.7 Dragging people risk

Milanesi, Pilotti & Ranzi [7] propose a model related, physically and quantitatively, to slipping, toppling, and drowning of a human body into flow field, where human body is conceptualised as a set of cylinders whose stability to slipping and toppling is analysed according to equilibrium forces and moments for different environments. Moreover, model takes into account the destabilizing effect of local slope and fluid density; that is why it allows a graded classification of hydraulic risk (Figure 5).

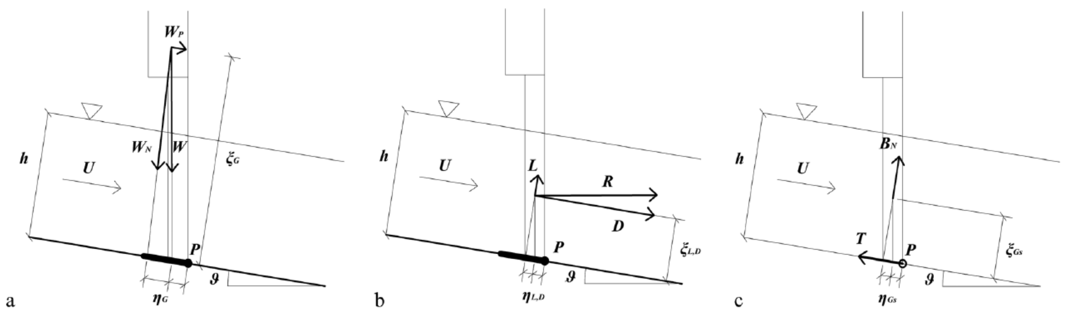

Fig. 5. Acting forces and their application points. (Source: [7])
W = body weight; W_N = normal component; W_P = parallel component, to the slope; R = fluid dynamic force; D = dynamic and parallel dragging force; L = dynamic and orthogonal lifting force; B_N = buoyancy force; T = friction; η_G y ξ_G = coordinates of the centre of mass of the body; $\eta_{L,D}$ y $\xi_{L,D}$ = coordinates of dragging and lifting forces applied on the submerged human body; h = water depth; U = mean water velocity.

Soriano [18], in turn, based on this criterion [7], further develops mathematical concepts to determine the dragging people risk index by applying Equation (1), valued between 0 and 1; in Table 5, Soriano [18] defines a hazard levels classification relating to values obtained from Equation (1).

Table 5: Flood hazard to people. (Source: [18]).

Value (HR)	Classification – Description
HR = 0	Secure (dry)
0 ≤ HR < 0.30	Very low hazard – be cautious
0.30 ≤ HR < 0.60	Low hazard – Includes people with disabilities
0.60 ≤ HR < 1.0	Medium hazard – Includes most of the population
HR ≥ 1.0 or hf ≥ hd	High – Includes everybody

HR = Flood hazard to people index; hd = drowning water depth threshold; hf = water depth.

$$HR = \min\left(1, \frac{U}{\min\left(U_{der}, U_{des}\right)}\right) \tag{1}$$

In which: HR = flood hazard to people index; Udes y Uder = critical velocities for instability due to friction, and destabilizing moments, in (m/s) respectively; U = water velocity, in (m/s), obtained from the hydrological-hydrodynamic simulation. Critical toppling velocity calculation Uder (in meters per second) and critical slipping velocity Udes (in meters per second) is calculated by using following equations:

$$U_{der} = \sqrt{\frac{4\left[WX_G - \rho g V_s\left(X_G + \frac{1}{2}Y_G sen2\vartheta\right)\right]}{C_C \rho A_s\left[hcos\vartheta + x_{G_s} sen2\vartheta\right]}} \tag{2}$$

Where: Uder = critical toppling velocity, in (m/s); CC = drag coefficient of a circular cylinder measured for uniform flow profile orthogonal to the body frontal area; W = bodyweight, in (kg_f); g = gravity acceleration, in (m/s^2); ρ = flow density, in (kg/m^3); As = wetted frontal area, in (m^2); Vs = submerged volume of the body, in (m^3); X_G = X coordinate of the body’s centre of gravity, in (m); Y_G = Y coordinate of the body’s centre of gravity, in (m); x_{Gs} = X coordinate of the centre of gravity of the submerged volume, in (m).

$$U_{des} = \sqrt{\frac{2\left(-Wtan\vartheta + W\mu - \mu g \rho V_S\right)}{C_C A_s \rho\left(cos^2\vartheta + \frac{1}{2}\mu sen2\vartheta\right)}} \tag{3}$$

Where: Udes = critical slipping velocity, in (m/s); CC = drag coefficient of a circular cylinder measured for uniform flow profile orthogonal to the body frontal area; W = bodyweight, in (kg_f); g = gravity acceleration, in (m/s^2); ρ = flow density, in (kg/m^3); As = wetted frontal area, in (m^2); Vs = submerged volume of the body, in (m^3); μ = friction coefficient, (adim).
Other parameters related to physical population characteristics of the study area were defined for an average Mexican adult, which are described in Table 6. To estimate dragging people risk exerted by the flow, it was necessary to use ArcGIS Model Builder tool to process rasters derived from simulation in Iber of water depth and velocity, extracted by one-hour time step intervals for return periods of 2 to 10,000 years, with corresponding DEM in tandem. For dragging people risk map generation, risk indexes were plotted according to Table 6 and Table 7.

Table 6: Average Mexican adult people physical characteristics. [19]

	Height (Y)	Weight (m)	Torso diameter (D)	Leg diameter (d)
	m	*kg*	*m*	*m*
Men	1.64	74.8		
Women	1.50	68.7		
Mean value	1.61	71.75	0.311	0.155

Table 7: Colour coding for creating dragging people risk maps.

N°	Letter	Risk index	Colour
5	A	High	
4	B	Medium	
3	C	Low	
2	D	Very low	
1	E	Safe	

Figure 6 describes processing performed and how are they linked in Model Builder once requested input parameters are entered: water depth raster and water velocity raster for a return period *i*, and a time step *j*, where each cell is evaluated to obtain the flood severity index. In steps II and III, for each velocity value per cell, four corresponding virtual water depths (y1, y2, y3 and y4) are calculated, where y1 corresponds to the boundary between the very low and low severity zones, y2 corresponds to boundary between low and medium severity zones, y3 corresponds to boundary between medium and high severity zones, and y4 corresponds to boundary between high and very high severity zones, boundaries depicted in Figure 4. In step V, a conditional evaluation was performed to compare cell by cell whether real water depth *Yi* is greater, less than, or equal to temporarily stored water depths y1, y2, y3, and y4, in order to categorise water depth severity level *Yi*, according to index values described in Table 4. The resultant raster is a raster containing severity indexes for a return period *i*, and a time step *j*.
Finally, for each *T i*, it is evaluated whether a cell in a raster of time step *j* has a greater value than value of that same cell of previous raster *j - 1* and make a substitution on previous raster until all the arrays have been compared, resulting in an array with maximum values.

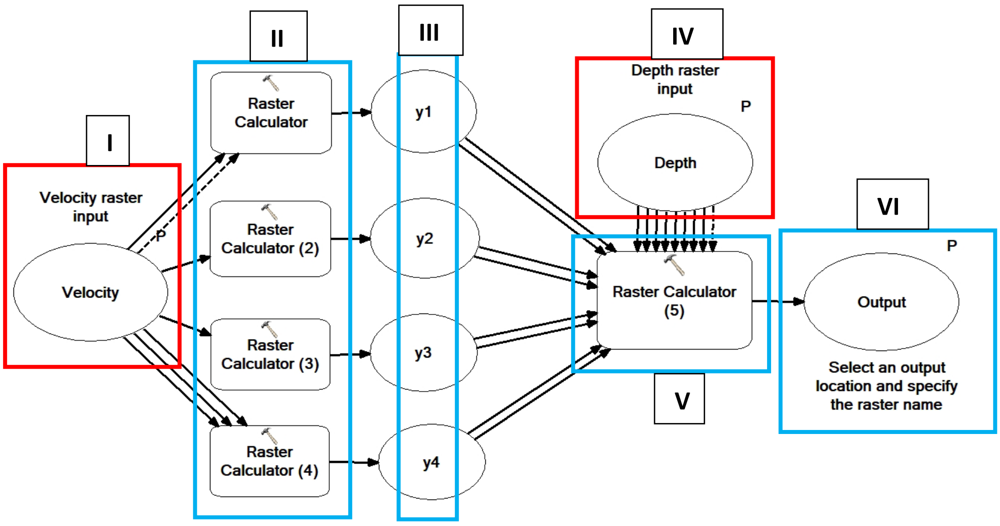

Fig. 6. Workflow diagram for flood severity index classification.

Similarly, to apply Milanesi criteria [7], Figure 7 describes processing performed and how are they linked in Model Builder once requested input parameters are introduced: water depth raster and the water velocity raster for a return period *i*, and a time step *j*, where each cell is evaluated to obtain people at risk index to being dragged by flooding, in tandem with a digital elevation model.
For step II, the variables related to the conceptualized representation of the human body such as the wetted frontal area and body submerged volume are calculated, defined as a function of human body height, torso diameter, legs diameter, and slope already determined from corresponding DEM. In step III, *Udes* and *Uder* (Equation 2 and 3, respectively) are estimated using a friction coefficient of 0.46 and a drag coefficient of 1; afterwards, both rasters with *Udes* and *Uder* values obtained are compared cell by cell to extract only minimum values, creating a third raster. In step IV, flood hazard to people index HR is obtained, which is equal to water velocity raster input divided by minimum critical toppling and slipping velocity; thus, values in a range of 0 to 1 are contained in resulting raster. In step V, all cells are reclassified according to Table 5 and Table 7 to obtain a final raster for a return period *i*, and a time step *j*.
This process is concluded by evaluating for each *T i* whether a cell in a raster of time step *j* has a greater value than value of that same cell on previous raster *j - 1* and make a substitution on previous raster until all arrays have been compared, resulting in an array with maximum values.

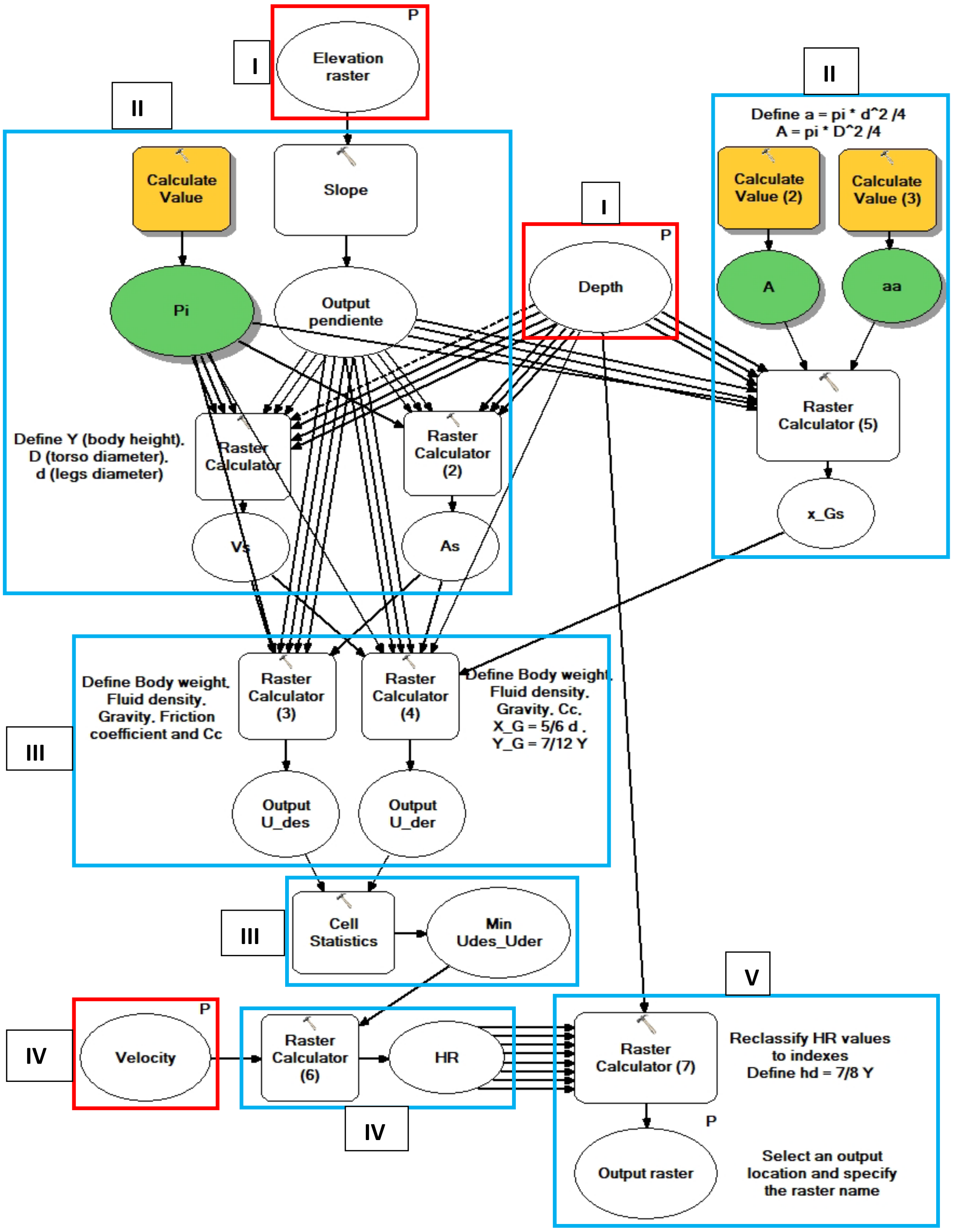

Fig. 7. Workflow diagram for the classification of the dragging people risk index.

3. Results and analysis

From Figure 8 to Figure 10 it is presented flood severity maps for a 100-year return period of Bosque Chapultepec's four sections; most of the area identified with flood severity within these four sections corresponds to hazard level E, which is described as a very low severity level (Table 4). In first and second sections of urban forest, for a return period of 100 years, about 83% of total affected area of approximately 1.39 km^2 corresponds to level E (Figure 8). For a *T* of 2 years and 10,000 years, approximately 82.78% and 80% correspond to severity level E respectively. On the other hand, for a 2-year *T*, 1.16% of affected areas is defined with a severity index A while for a 10,000-year *T* this index represents 1.11% of total affected area. Areas with a very high severity for a 100-year *T* are mostly visible in Miguel Hidalgo borough, on intersection of Cto. Interior Melchor Ocampo and Paseo de la Reforma Ave, on junction of Rubén Darío St, Calzada Chivatito and

Arquímedes St, and on Morvan St; also, in Cuauhtémoc borough on Lieja St, an underpass crossing Paseo de la Reforma Ave (Figure 8).

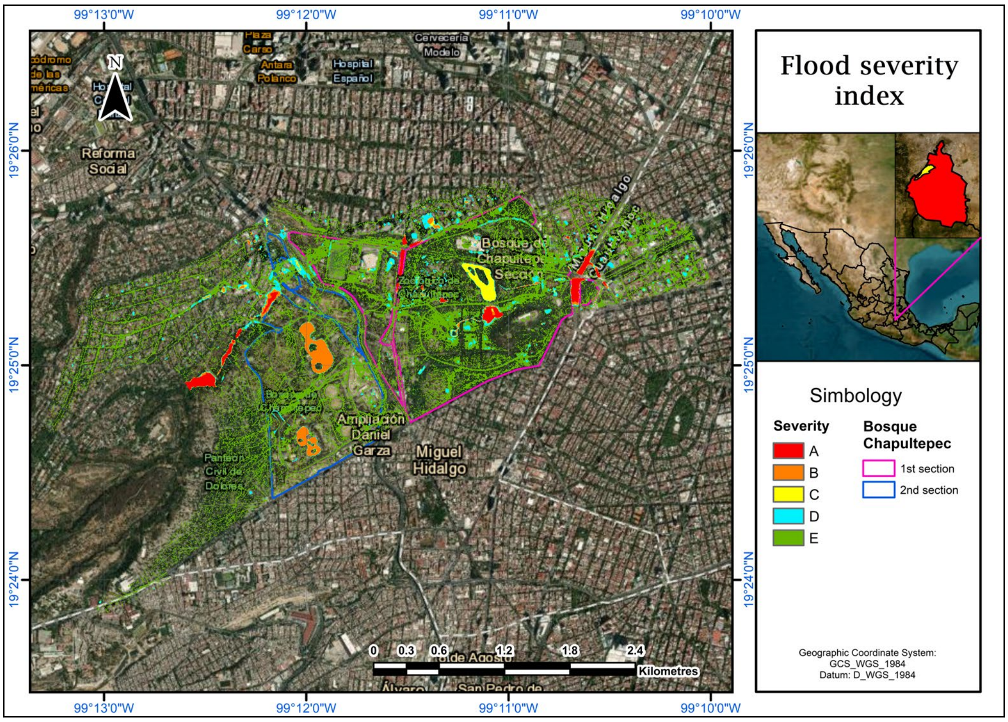

Fig. 8. Flood severity on 1st and 2nd sections of Bosque Chapultepec, for a 100-year return period.

In third section of Bosque Chapultepec, it was observed that for all return periods evaluated, about 70% of affected areas had a severity level E. Affected areas with a severity index A for a 2-year *T* accounted for 8.9% of the total, and for a 10,000-year *T* it increases by 2%. For a 100-year *T*, most of areas with very high severity correspond to Dolores dam and natural channels that discharge into it, in Miguel Hidalgo borough (Figure 9).

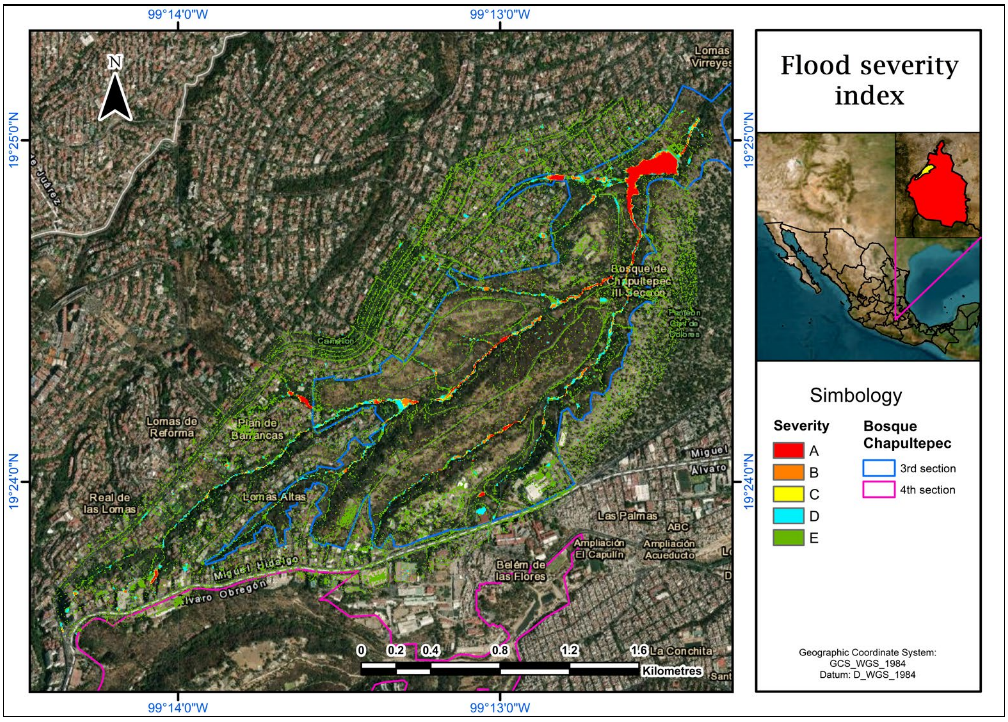

Fig. 9. Flood severity on 3rd section of Bosque Chapultepec, for a 100-year return period.

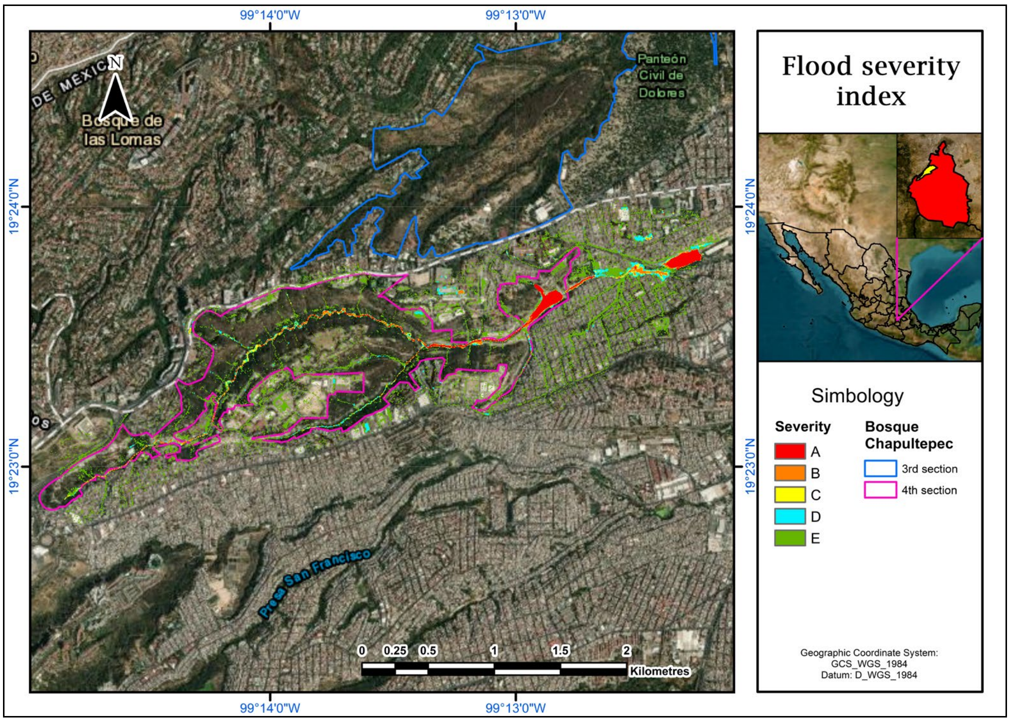

Fig. 10. Flood severity on 4th section of Bosque Chapultepec, for a 100-year return period.

In the fourth section it was observed that for a 100-year *T* there is a total affected area of 0.22 km^2, about 62.3% corresponds to severity level E (Figure 10); for a *T* of 2 and 10,000 years there is an affected area of 67.4% and 60.4% respectively with severity level E. For a 2-year Tr, 0.74% of the total area affected reaches a severity index A, and for a 10,000-year *T* it rises by 17%. These areas with a high severity are mainly displayed at Tacubaya dam, as well as its downstream subarea where the discharge water is conducted from the dam's outlet work to Mexico City drainage network plus, on Ruiz Cortines dam and into Tacubaya River, in Álvaro Obregón borough of (Figure 10). Figure 11 to Figure 13 show 100-year return dragging people risk maps for the four sections of bosque Chapultepec; most of area identified as people in risk of being washed away corresponds to dragging risk level D, which is described as a very low risk level, but caution should still be exercised (Table 5).

Particularly, in the forest's first and second sections, for a 100-year *T* of total area at risk which is about 1.92 km^2 (represented in Figure 11) approximately 95.26% corresponds to a risk level D. For a *T* of 2 years and 10,000 years, about 98.5% and 93.6% correspond to the risk level D respectively. Furthermore, for a 2-year *T*, 0.17% of affected areas are defined with a risk level A while for a 10,000-year *T* it represents 1.43% of total affected area. For a 100-year *T*, these areas with a high drag risk are mainly exhibited on Calz. Mahatma Gandhi continuing towards Parque de la Amistad and Calz. General Mariano Escobedo, on main access ramp to Chapultepec Castle in first section of the urban forest, also on Paseo de la Reforma Ave on north side of National Auditorium and military Marte Field, on Calz. Chivatito, and to west side of the former Feria de Chapultepec on De los Compositores Ave turning towards Rodolfo Neri Vela Ave; in Miguel Hidalgo borough (Figure 11).

It was observed in third section of urban forest that for a *T* of 100 years, 0.68 km^2 were affected, where a little more than 93.1% corresponds to risk level D (Figure 12). For a *T* of 2 years and 10,000 years, approximately 95% and 92% of total affected area correspond to a risk level D respectively. As for the risk index A, for a 2-year *T* affected areas correspond to 2.34% of total, and for a 10,000-year *T* correspond to 4.18%. For a 100-year *T*, most of the areas with a high dragging people risk were primarily in natural channels that discharge into the Dolores Dam, as well as at the entrance of the dam and in its discharged downstream, in Miguel Hidalgo borough (Figure 12).

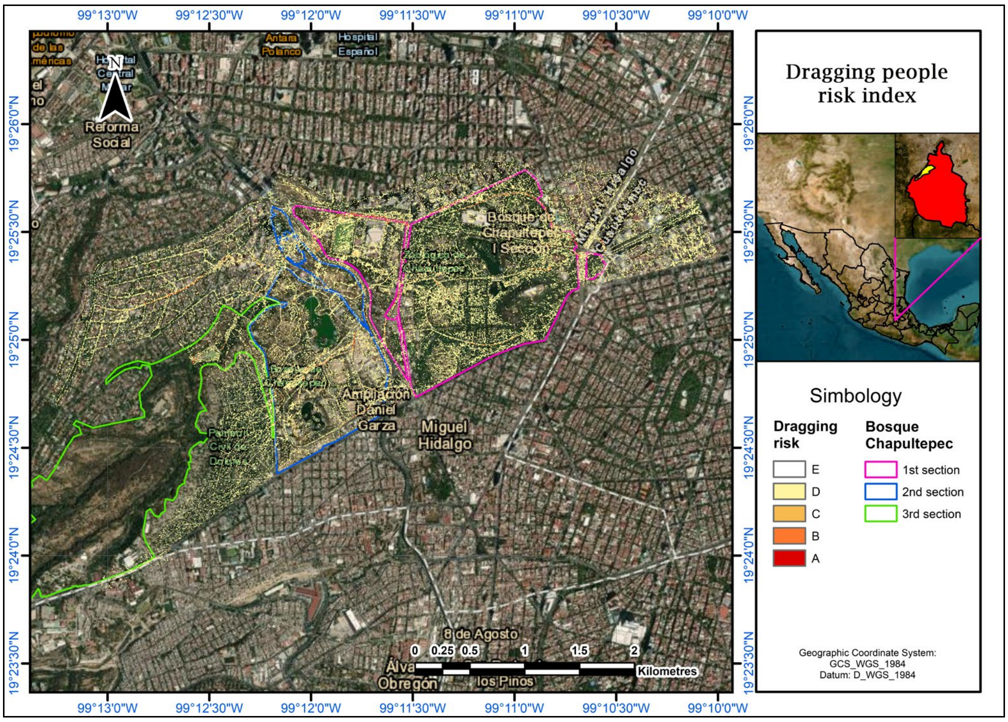

Fig. 11. Dragging people risk on 1st and 2nd sections of Bosque Chapultepec, for a 100-year return period.

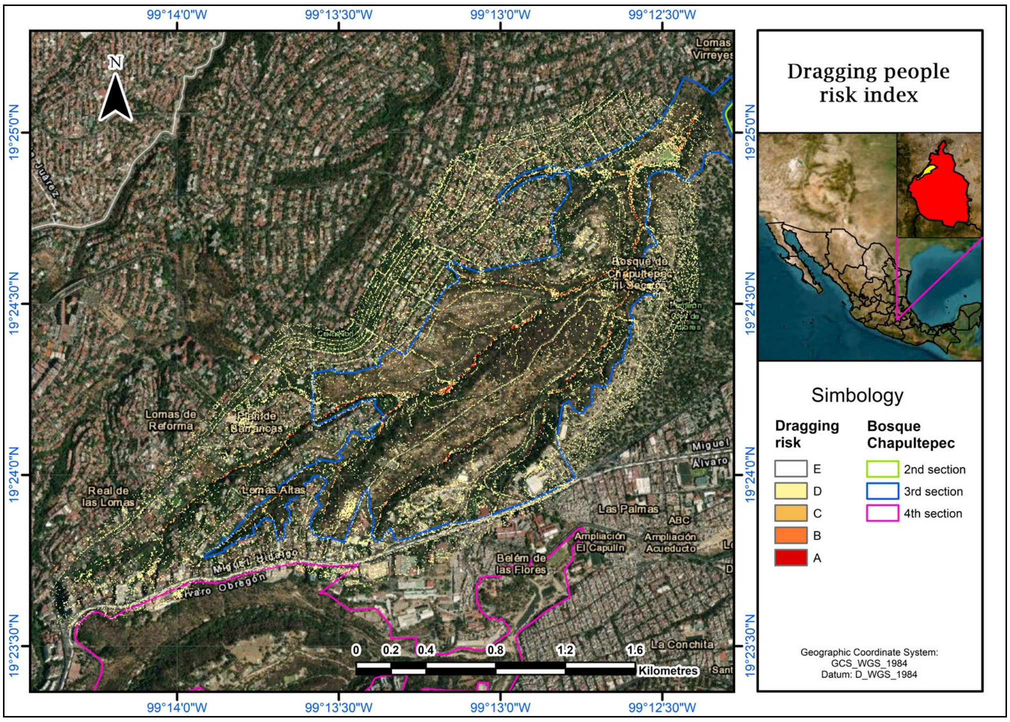

Fig. 12. Dragging people risk on 3rd section of Bosque Chapultepec, for a 100-year return period.

Lastly, in the fourth section of Bosque Chapultepec, a total affected area of 0.58 km^2 was obtained for a 100-year *T*, and about 90.6% of it relate to a drag risk level D (Figure 13); for a *T* of 2 and 10,000 years there is an affected area of 92.1% and 90% respectively displaying this same level of risk. However, at risk level A, affected areas for a 2-year *T* accounted for 6.76% of the total, and for a 10,000-year *T* accounted for 9.62%. These zones with high drag risk are mainly located at various points along Tacubaya River, which discharges into Tacubaya Dam, and these zones continue in superficial runoff towards to Ruiz Cortines Dam despite the fact that Tacubaya Dam discharges through an outlet structure downstream connected to Mexico City drainage network; similarly, on Río Santo Domingo and Presidente Juárez streets, in Álvaro Obregón borough (Figure 13).

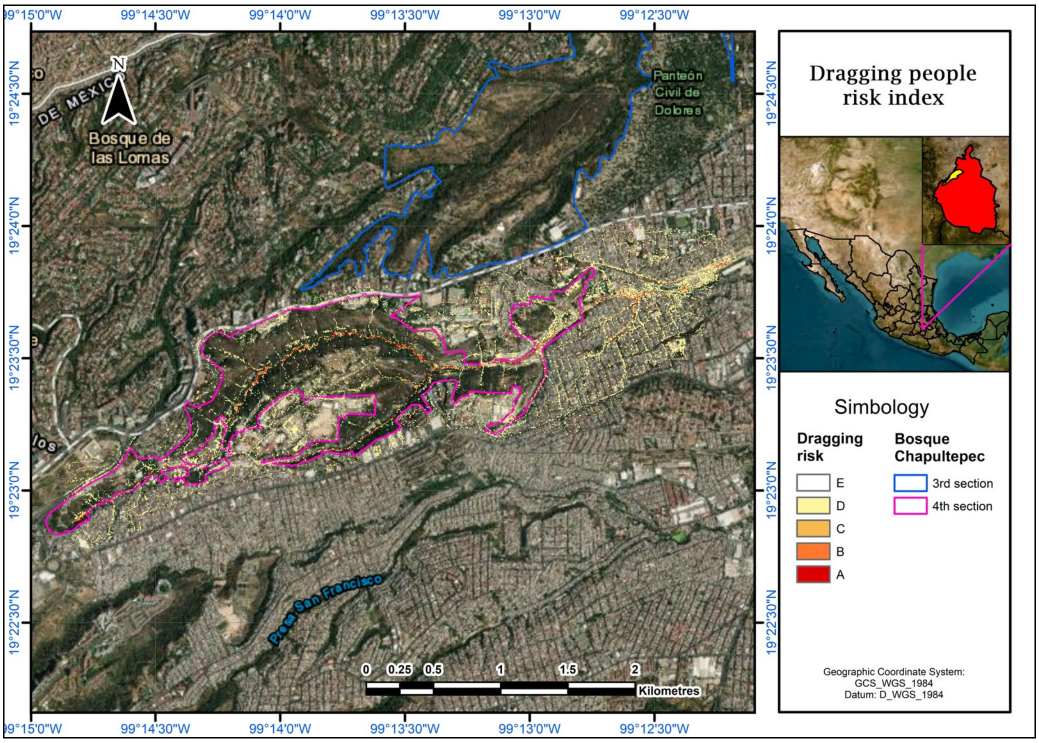

Fig. 13. Dragging people risk on 4th section of Bosque Chapultepec, for a 100-year return period.

4. Discussion

A medium to high level of people risk to being washed away was mainly presented in natural channels, especially in 3rd and 4th sections, and on some streets and footpaths within 1st and 2nd sections, indicating that most of the population would be vulnerable during a storm event.
In case of 3rd and 4th sections, both are micro-basins with runoff generating on roads but quickly concentrating into rivers that discharge to Dolores Dam and Tacubaya Dam. Nonetheless, 1st and 2nd sections have more streets that reduce surface runoff volume entering permanent water bodies, where flow direction is determined by its slope itself, concentrating to local runoff towards areas with steepest slopes. From a variation analysis of drag risk and flood severity levels throughout all areas affected obtained by both methods, it was observed that change in percentage in distribution of each level of severity and risk of people being dragged changed minimally. For example, areas with severity or drag risk type A remain almost the same for a 10,000-year *T* compared to the 2-year *T*, there is a proportional expansion between return periods; in other words, between the 2-year and 10,000-year *T*, there is practically the same level of flood risks for the same area.

5. Conclusions

The software Iber facilitated hydrodynamic models generation to study the runoff process during and after a storm event (for return periods of 2 to 10,000 years) in Chapultepec's four sections. The ArcGIS Model Builder tool made it easy to integrate data from extracted rasters plus the MDE to significantly reduce the processing time required for generating flood severity and dragging people risk maps.
This paper utilized two methodologies focusing on population risk (Milanesi's criterion) and considering infrastructure and vehicles (Dorrigo's criterion). By applying Dorrigo criterion for each pixel with a depth and velocity value, a flood severity index is obtained. A medium to high severity

occurred especially where there were bodies of water, natural channels, or underpasses. When implementing Milanesi criteria, defining population's anthropometric characteristics is an important factor to characterise aftereffects on our study area; hence, population physical parameters were specified in accordance with average values of the central region of the country, which was only information available for the past 10 years. Furthermore, slipping or toppling velocities are dependent on runoff depth and terrain slope, which in comparison to applying Dorrigo approach for processing water depth and velocity rasters, a value of slipping or toppling velocity is not obtained in all cells of these rasters; therefore, not all runoff results in people being dragged, but it may cause drowning which severity maps can identify.
Finally, it is recommended to plan road closures and create evacuation routes within recreational areas of Bosque Chapultepec in case of emergency due to storms and/or flooding, which show to visitors the way to the nearest pre-assigned meeting locations inside or outside the immediate area, as well as the nearest exits of the forest. It should be noted the possibility of expanding social programs for garbage collection in surrounding areas to this urban forest, which frequently obstruct Mexico City's drainage system both at entrance to drainage and in conduction system, and to make visitors aware to use garbage deposits properly and continuously since there are several commercial areas that increase proliferation of inorganic garbage within the forest.

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