Transactions on Energy Systems and Engineering Applications

Article

Statistical Analysis to Quantify the Impact of Map Type on Estimating Peak Discharge in Non-Instrumented Basins

Alexandra Sierra-Sánchez[1], Óscar E. Coronado-Hernández[1,*], Duban A. Paternina-Verona[1], Gustavo Gatica[2], and Helena M. Ramos[3]

[1] Facultad de Ingeniería, Universidad Tecnológica de Bolívar, Cartagena de Indias 131001, Colombia.
[2] Faculty of Engineering – CIS, Universidad Andres Bello, Santiago de Chile 7500971, Chile.
[3] Department of Civil Engineering, Architecture and Georesources, CERIS, Instituto Superior Técnico, University of Lisbon, 1049-001 Lisbon, Portugal.
[*] Correspondence: ocoronado@utb.edu.co

Received: 5 June 2023; Accepted: 26 July 2023; Published: 11 August 2023

Abstract: The calculation of peak discharge in non-instrumented basins requires including morphometric parameters, which in turn depend on the map type used. This study analyses the impact of and variation in peak discharges of the Caño Ricaurte basin, Colombia, based on three types of maps at different resolution scales. The reference map used was the map made for the detailed designs of the channel analysed, which was extracted from the Master Plan of the City. Additionally, maps from a 90 × 90 m digital elevation model and contour lines extracted from Google Earth were used. The time of concentration was determined by different equations (Kirpich, Témez, Bureau, and TR-55) using the mapping methods described above, and the peak discharge was determined using rainfall-runoff models.

 https://doi.org/10.32397/tesea.vol4.n2.522

1. Introduction

To determine the behaviour of hydrological natural disasters (floods) in lotic systems without hydrometric stations, rainfall-runoff models are used, which begin by analysing the extreme rainfall event and end with determining the peak runoff [1]. These floods represent a socioeconomic problem in cities since they directly affect the population and the existing infrastructure. For this reason, a detailed study of the morphometric parameters in non-instrumented basins is necessary for determining the maximum rate of flow (peak discharge) that would provide reliability to the infrastructure designed.

One of the most important characteristics of urban watersheds is their low infiltration index and high permeability coefficient, causing an increase in the peak discharge for infrastructure works. These flows

How to cite this article: Sierra-Sánchez, Alexandra; Coronado-Hernández, Óscar E.; Paternina-Verona, Duban A.; Gatica, Gustavo; Ramos, Helena M.;. Statistical Analysis to Quantify the Impact of Map Type on Estimating Peak Discharge in Non-Instrumented Basins. *Transactions on Energy Systems and Engineering Applications*, 4(2): 522, 2023. DOI:10.32397/tesea.vol4.n2.522

depend on the morphometric characteristics of the basin, the management of rainfall data, and the correct application of the regulations [2]. Several methodologies have been proposed to obtain peak discharge using this type of model.

Geographic information tools and satellite imagery can be used to identify the morphometric parameters of watersheds. Terrain elevation models have provided good approximations and consistent results for obtaining these parameters, providing accurate data [3,4].

The delimitation of a watershed and the determination of the morphometric parameters can vary depending on the map scale. Different methodologies in the literature [5] have also been used to determine the time of concentration. Therefore, methodologies regulated by current regulations should be chosen that adequately adjust to the topographic conditions of the piped or channel system [6]. The calculation of the time of concentration is one of the most important parameters for rainfall-runoff modelling. Mudarishu et al. [5] evaluated the time of concentration of different urban sub-basins of Sungai Kerayong, Kuala Lumpur, with small slopes and areas between 13.7 and 20.7 km2, where the authors evaluated the hydrological response with measurements through rainfall data and compared the calculated values of the times of concentration with the values observed in storms, showing that the times of concentration calculated with the Gundlach, Carter, and NAASRA methods, presented similar values in comparison with observed values. On the other hand, Sandoval and Aguilera [7] calculated the time of concentration of different basins in Ecuador using the Kirpich, Témez, Chow, Giandotti, and Goroshkov equations to determine different equations for the calculation of peak flow for watersheds without hydrological data. Bisantino et al. [8] developed a hydrological model for a medium-sized watershed under semiarid conditions, where the authors calibrated their model by applying a sensitivity analysis based on their current conditions and assigning model parameters, with parameters such as the curve number being one of the determining factors in the prediction of runoff peaks over the watershed. Ramos and Coronado-Hernández et al. [9] showed the application of the Internet of Things in hydroelectric power stations for hydrological purposes. Gericke and Smithers [10] performed a review of different equations for the estimation of time of concentration in South African basins, in which the authors calculated the time of concentration of different basins by comparing the distribution of time of concentration vs. area recommended in the study, filtering out equations that over-estimate or under-estimate the time of concentration in these basins.

Drainage areas and time of concentration determined by digital elevation models (DEMs) and contour lines from Google Earth can vary significantly, which generates different peak discharges [11–16]. Cartagena de Indias has a flat topography that contributes to flood problems, leading to annual human and economic losses that affect 71% of the population [17]. The Caño Ricaurte basin is one of the largest urban basins of Cartagena and has flooding problems in several sections, even during rainfall events with an annual return period. This basin has problems related to unregulated and progressive urban growth and invasion into retention and channelled areas, which causes flooding in the middle and lower sections of the Ricaurte canal [18].

Under this framework, this work aims to identify and capture the most impactful morphometric parameters for peak discharge at different return periods based on various maps created from DEM models and contour lines generated from Google Earth Pro, using as ground truth the data calculated in the works referenced by the Master Plan of Cartagena de Indias [16]. Different GIS tools such as ArcGIS 10.5, Web GPS Visualizer, and Google Earth Pro and hydrological modelling in HEC-HMS 4.3 were applied. Results can be used to understand the variation of peak flows associated with various return periods considering not only different map types but also different formulations to compute the time of concentration in a watershed.

2. Methods and Materials

2.1. Methodology

2.1.1. Basin delimitation

In the initial phase, two methodologies were used to delimit the basin: the first one, using contour lines extracted from Google Earth (GE), obtained from the GPS Visualizer web page; and the second one, using the information of the 90x90 Digital Elevation Model (DEM) available from the United States Geological Survey. Delimitation of the basin was performed using ArcGIS 10.5 for both methods. In addition, the information on the Master Plan of the City of Cartagena was used to calculate the watershed delineation.

2.1.2. Time of concentration

Considering the importance of time of concentration in obtaining adequate rainfall-runoff model results, the Kirpich, Bureau, Teméz, and NRCS (TR-55) methods were used to determine the importance of these parameters (axial length, elevation difference, average slope, and maximum 24-hr rainfall associated to a return period of 2 years). Kirpich developed an empirical equation based on background information from seven (7) American rural watersheds [19], applicable to medium-sized watersheds, with considerable slopes and designed for cultivated soils. With the equation developed by Kirpich, the time of concentration T_c (in minutes) can be calculated as

$$T_c = 0.0195L^{0.77} * S^{-0.385} \quad , \tag{1}$$

where L is the axial length of the channel (m); and S is the average slope of the channel (m/m).

Bureau developed an empirical equation based on background information from California mountain basins [20], given by

$$T_c = 60 * \frac{(0.871 * L/\Delta H)^{0.385}}{60} \quad , \tag{2}$$

where ΔH is the elevation difference, in m.

The Teméz method was applied for basins of 1 km^2 to 3000 km^2 and applicable for time of concentrations between 15 minutes and 24 hours [20]. With this method, the time of concentration can be calculated as

$$T_c = 0.30 * (\frac{L}{Sm^{0.25}})^{0.77} \quad , \tag{3}$$

where Sm is the average slope, in %.

Finally, the publication of the Technical Release 55 (TR-55) calculates the time of concentration as the sum of several travel times in the drainage system. This methodology defines three travel times that are identified in any basin:

- Sheet flow: this is flow over plane surfaces and generally occurs in the headwaters of streams. The travel time for sheet flow T_{t1} (in hours) can be calculated by

  $$T_{t1} = \frac{0.002886(nL)^{0.8}}{(P_2/1000)^{0.5} * S^{0.4}} \quad , \tag{4}$$

  where L is flow length, in m; and P_2 is the maximum 24-hr rainfall associated to a return period of 2 years, in mm.

- Shallow concentrated flow: The travel time for shallow concentrated flow T_{t2} (in hours) is given by

$$T_{t2} = \frac{L_g}{3600V} \ , \tag{5}$$

where L_g is flow length in m, and V is the average velocity in m/s, which can me calculated by

$$V = 6.91976\sqrt{S} \ , \tag{6}$$

for paved surfaces, and by

$$V = 4.919\sqrt{S} \ , \tag{7}$$

for unpaved surfaces.

- Open channel: To determine the average flow velocity (V) in the channels, Manning's equation or the flow profiles can be used, selecting the wetted perimeter for its determination [21]. The travel time for open channel flow T_{t3} (in hours) can be calculated as

$$T_{t3} = \frac{L_g}{3600V} \ . \tag{8}$$

2.1.3. Calculation of the curve number

The curve number was determined with the geographic information system of the environmental observatory of Cartagena, using the images corresponding to the lithology and land use of the study area. With the lithology corresponding to each soil and the soil groups classified by the Soil Conservation Service (SCS), the group was assigned to each subbasin.

Similarly, for the runoff curve number (CN), the type of land assigned by the Land Use Plan (POT, in Spanish) of Cartagena [22] and the equivalent number proposed for each use by Pérez [18] were taken into account. The characteristics of the Curve Number did not vary in this research.

2.1.4. Rainfall

The data used for the analysis of the frequency of the 24-hour maximum rainfall were obtained from the records available in the IDEAM, selecting the main synoptic station Rafael Núñez Airport because of its proximity to the study basin and robustness of information. The 24-hr maximum rainfall values for return periods of 5, 10, 25, 50, and 100 years were obtained from the publication by Gonzalez-Alvarez et al. [23], which considers the effect of climate change using non-stationary functions. The 24-hr maximum rainfall was reduced to a 3-h extreme rainfall based on the analysis of the pluviographic records of the station. Similarly, the temporal distribution of the 3-hr rainfall was used [21]. The results of the publication were used in this research.

2.1.5. Rainfall-runoff modelling

Rainfall-runoff modelling was performed using a semi-distributed model (by subbasins) using HEC-HMS 4.3. For the modelling, the SCS methods were used to calculate the infiltration losses, the SCS unit hydrograph, and the Muskingum Cunge model to make the transit through the channel sections, which have been widely used to study the hydrological behaviour in these areas.

For the GE model in subbasins GE-1, GE-7, and GE-8, for the DEM model in subbasins DEM-1 and DEM-8, and finally, in the Master Plan basin in the subbasins A1, A9, and A10, it is necessary to calculate a new flood travel time, given that in the modelling in the programme, the main channels correspond to flow travel.

2.1.6. Statistical analysis

To compare the different methodologies, the delimitation of the drainage basin of the Drainage Master Plan (MP) of Cartagena and the time of concentration determined by the methodology proposed by the NRCS (TR-55) were used as reference information [21]. These values served as a reference to compare the peak flow rates obtained with this methodology with those obtained from the delimitation of the basin with the GE and DEM models and with the Kirpich, Témez, and Bureau equations for calculating the time of concentration.

Figure 1 summarizes the used methodology in this research.

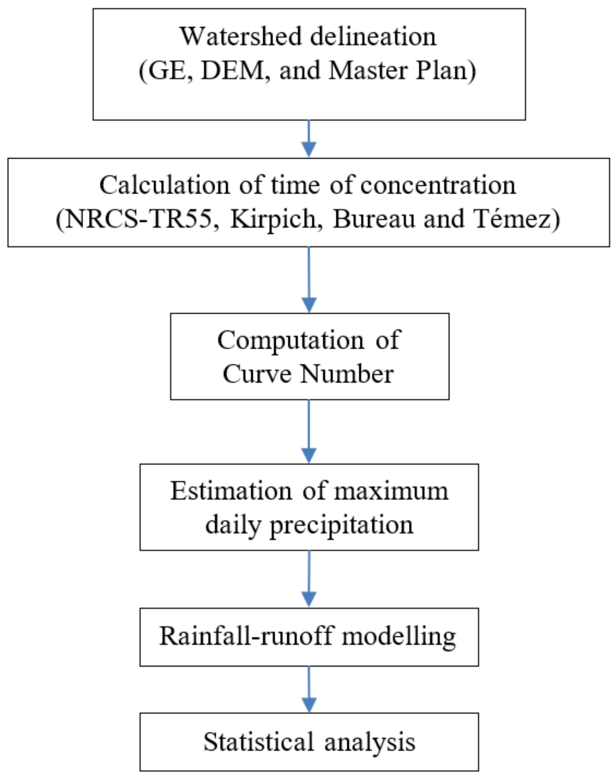


Figure 1. Methodology flowchart.

2.2. Case study

The Caño Ricaurte basin, located in Cartagena, Bolívar, Colombia, is one of the urban basins making up this city. This basin drains to the Ciénaga de la Virgen (see Figure 2). The Caño Ricaurte is made up of several sectors, among which are: El Socorro, Emiliano Alcalá, Blas de Lezo, San Fernando, Chiquinquirá, Juan José Nieto, Las Gaviotas and the Ricaurte sector itself [24].

The morphometric parameters of the Caño Ricaurte basin were obtained based on the information available from the District Valuation Office [25] of the District of Cartagena de Indias. These parameters are presented in Table 1.

The time of concentration was determined for each of the reference subbasins of the study using the available information from the District Valuation Office [25], whose results are shown in Table 2.

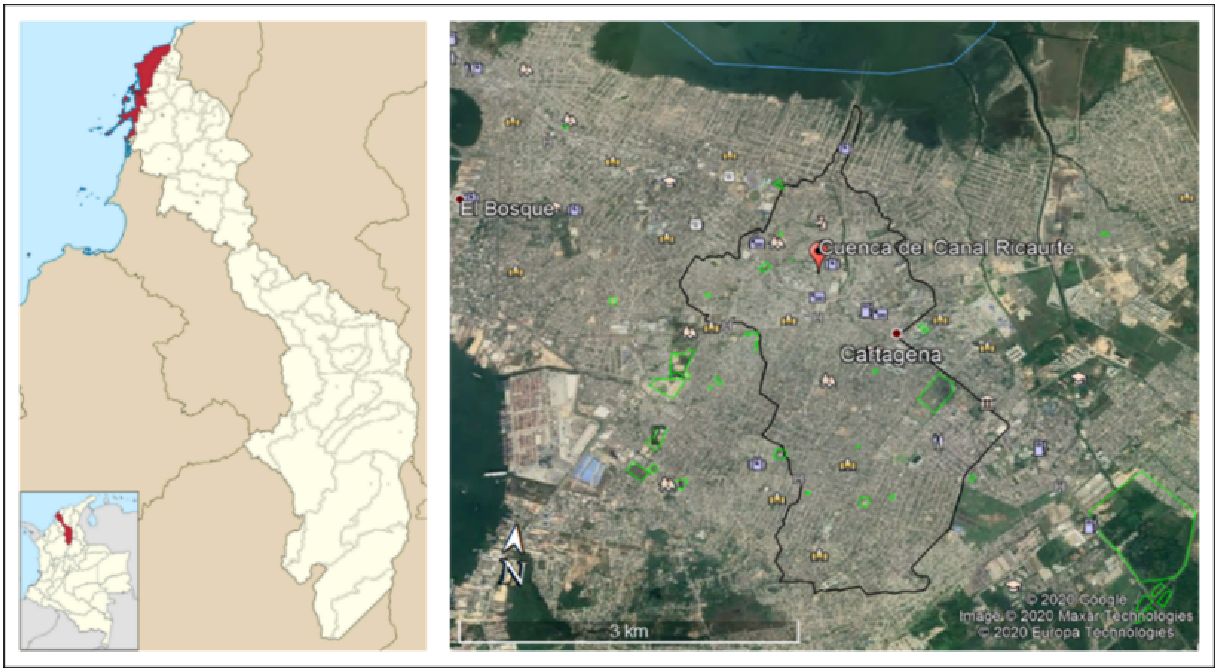


Figure 2. Location of the Caño Ricaurte basin.

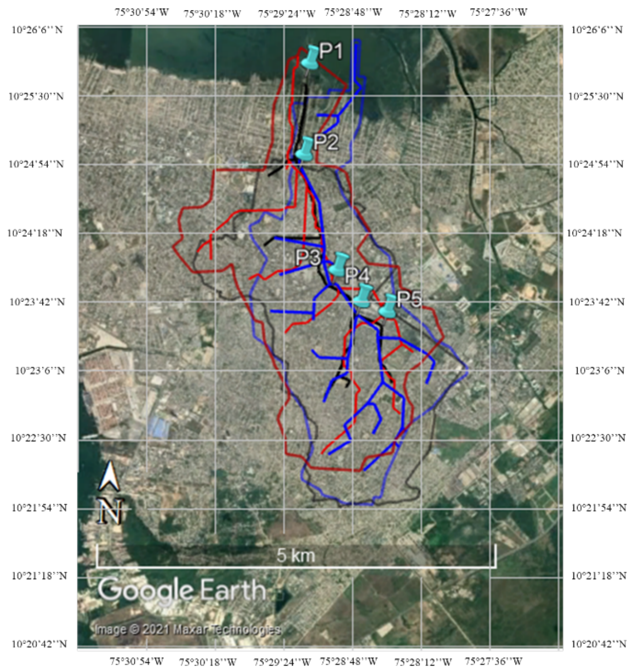
Parameter	Value	Units
Area (A)	7.46	km^2
Perimeter (P)	22.09	km
axial length (L)	4.38	km
Basin width (B)	1.56	km
Length of the main channel (L_c)	5.60	km
Max. Height	65.00	m
Min. Height	4.00	m
Slope of the basin	0.90	%

Table 1. Morphometric parameters of the Caño Ricaurte basin [17].

Sub-basin	Tc Kirpich (hour)	Tc Bureau (hour)	Tc Teméz (hour)	TR-55 (hour)
A1	1.528	0.793	0.820	0.63
A10	0.353	0.391	0.234	0.13
A2	0.559	0.672	0.251	0.29
A3	0.441	0.364	0.275	0.42
A4	0.574	0.378	0.377	0.97
A5	0.617	0.394	0.379	1.00
A6	0.633	0.425	0.530	0.27
A7	0.609	0.504	0.403	0.29
A8	0.263	0.393	0.170	0.49
A9	0.252	0.314	0.143	0.11

Table 2. Time of concentration for the reference basin [17].

The correlation coefficient (R^2) was used as a measure of goodness of fit, taking as reference points those presented in Figure 3.



Point	Coordinates	
	Latitude	longitude
P1	10°24'56.89''N	75°29'17.66''O
P2	10°24'19.24''N	75°29'18.05''O
P3	10°23'32.53''N	75°29'1.83''O
P4	10°23'20.17''N	75°28'5133''O
P5	10°23'16.37''N	75°28'40.27''O

Reference points
GE
DEM
Master Plan

Note: The drainage network of each model corresponds to the darkest lines in the map, more transparent lines correspond to the area of each model.

Figure 3. Location of the reference points over the area of the Caño Ricaurte basin in each model.

3. Analysis of Results

The delimitation obtained through the referenced points extracted from Google Earth Pro and processed in ArcGIS 10.5 generates a basin with an area of 7.658 km^2 and a perimeter of 15.26 km; a maximum elevation of 50 m and a minimum of 2 m, where its main channel ends, whose length is 5.21 km. Nine major subbasins drain over the main channel, which are named GE-1, GE-2, GE-3, GE-4, GE-5, GE-6, GE-7, GE-8, and GE-9, as shown in Figure 4.

The time of concentration for the GE model using the Bureau equation gives as a result 1.26 hours, for Kirpich 1.89 hours, and for Témez 1.05 hours, presenting on average a difference of 0.73 hours. The morphometric parameters were calculated for the general basin model (see Table 3) and for each subbasin (see Table 4); through these parameters, it was possible to calculate the T_c of each subbasin.

Parameter	Value	Units
Area (A)	7.6528	km^2
Perimeter (P)	15.26	km
axial length (L)	5.013	km
Basin width (B)	1.53	km
Length of the main channel (L_c)	5.21	km
Max.	50	m
Min height	2	m
Slope of the basin	0.974	%

Table 3. Morphometric parameters of the GE model.

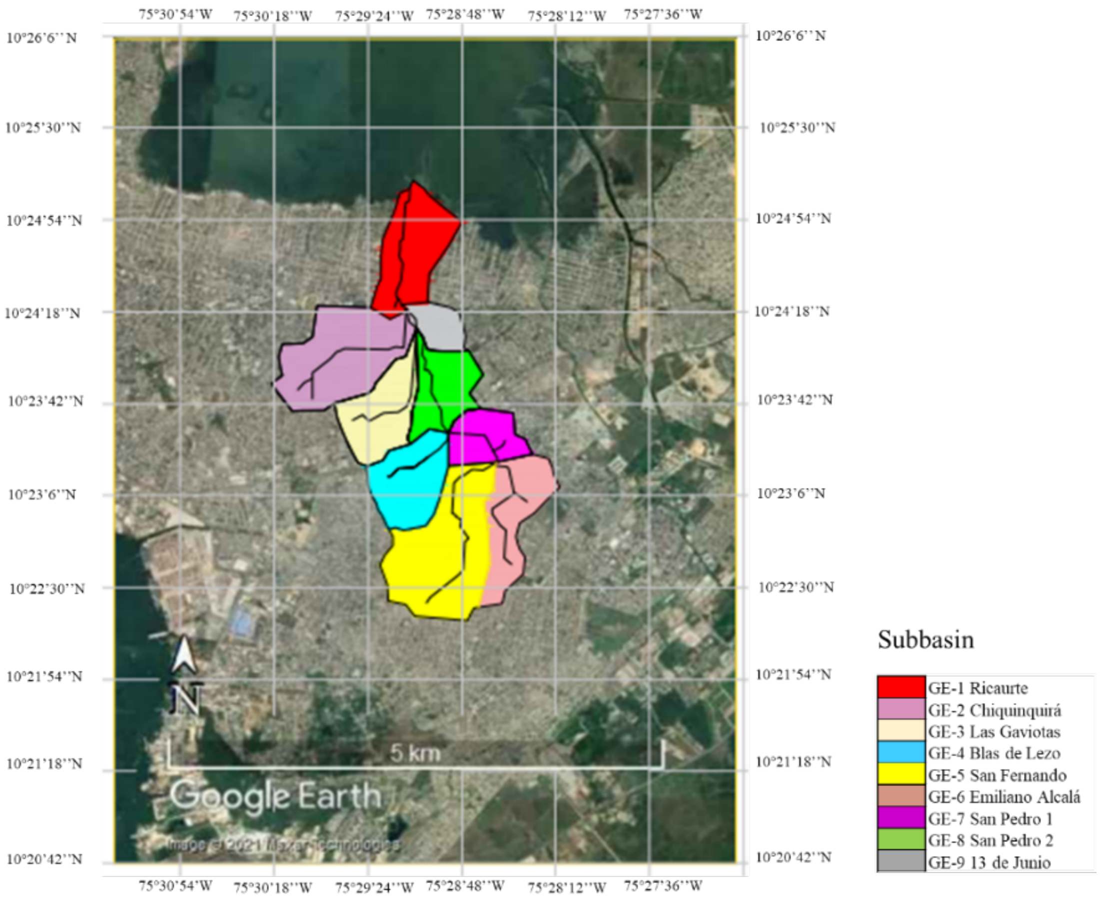


Figure 4. Subbasins for the GE model, with their respective identification.

Sub-basin	Area (A) km^2	Perimeter (P) km	Axial length (L) km	Length of the main channel (L_c)	Length of branch channels	Time of concentration			
						T_c Kirpich (Hour)	T_c Bureau (Hour)	T_c Teméz (Hour)	T_c NRCS (TR-55) (Hour)
GE-1	0.9098	4.34	1.43	1.43	1.547	0.819	0.665	0.507	0.22
GE-2	1.3466	4.94	2.064	1.92	2.145	0.796	0.638	0.478	0.23
GE-3	0.7738	4.23	1.814	1.66	1.66	0.11	0.08	0.107	0.73
GE-4	0.7776	3.824	1.163	0.939	1.031	0.567	0.418	0.407	0.52
GE-5	1.5937	5.64	2.49	2.29	2.29	0.72	0.67	0.565	1.00
GE-6	0.835	4.75	1.71	1.52	1.52	0.446	0.305	0.288	0.42
GE-7	0.4859	2.58	0.78	0.78	0.981	0.545	0.305	0.322	0.1
GE-8	0.6381	4.00	1.38	1.38	1.38	0.939	0.615	0.53	0.22
GE-9	0.2932	2.33	0.345	0.345	0.345	2.13	0.793	0.863	0.15

Table 4. Morphometric parameters and time of concentration for the subbasins of the GE model.

The delimitation obtained through the DEM and processed in ArcGIS 10.5 results in a basin with an area of 5.71 km^2 and a perimeter of 12.94 km; a maximum elevation of 56 m and a minimum of 2 m where its main channel ends, whose length is 5.21 km. Nine major subbasins drain over the main channel, which are named DEM-1, DEM-2, DEM-3, DEM-4, DEM-5, DEM-6, DEM-7, DEM-8, and DEM-9 (as shown in Figure 5).

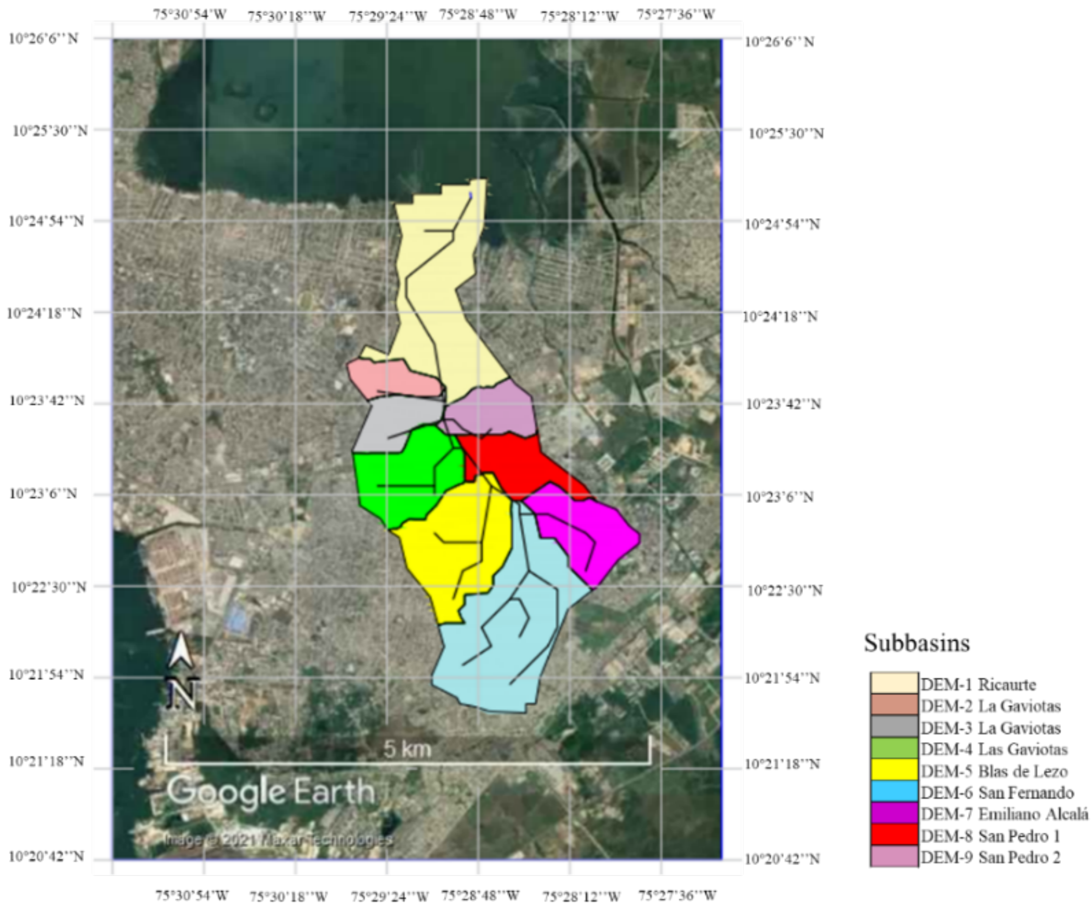


Figure 5. Subbasins for the DEM model, with their respective identification.

The time of concentration for the DEM model using the Bureau equation yields 1.39 hours, for Kirpich 2.66 hours, and for Témez 1.04 hours, presenting on average a difference of 1.45 hours between each of the equations. The morphometric parameters were calculated for the basin model in general (see Table 5) and in turn for each of the established sub-basins (see Table 6); through these parameters, it was possible to calculate the T_c of each of them.

From the results obtained, there are several differences that we found between the GE and DEM basin models. In comparison to the DEM model, the GE model shows increases in the area (34%), perimeter (15.2%) and width of the basin (51.8%). Regarding the main channel, the models have the same length, which is the strongest current shown by the programme. Similar to the final height of each model, both are 2 m above sea level.

The variation in the results is due to the different errors that occur within each of the procedures in the systems and each of the components of the cartographic files; errors due to defects in the DEM, from georeferenced points in Google Earth Pro to the handling of these in ArcGIS 10.5.

Within the DEM model used, the vertical and horizontal accuracy depends on the place where it was extracted and varies according to the roughness of the relief [16]. In the case of the contour lines, these

Parameter	Value	Units
Area (A)	5.7139	km2
Perimeter (P)	12.9400	km
Axial length (L)	5.6714	km
Basin width (B)	1.0075	km
Length of the main channel (Lc)	5.2193	km
Maximum height	56.0000	m
Minimum height	2.0000	m
Slope of the basin	1.0320	%

Table 5. Morphometric parameters of the DEM model.

						Time of concentration			
Sub-basin	Area (A) km^2	Perimeter (P) km	Axial length (L) km	Length of the main channel (L_c)	Length of currents	T_c Kirpich (Hour)	T_c Bureau (Hour)	T_c Teméz (Hour)	T_c NRCS (TR-55) (Hour)
DEM-1	1.27	6.47	2.32	2.3	2.98	0.62	0.79	0.81	0.87
DEM-2	0.21	2.13	0.91	0.59	0.59	0.17	0.29	0.22	0.22
DEM-3	0.28	2.49	0.77	0.53	0.53	0.13	0.23	0.19	0.3
DEM-4	0.58	3.18	1.12	1.17	0.99	0.22	0.29	0.38	0.57
DEM-5	0.84	4.07	1.45	1.12	1.57	0.16	0.35	0.29	0.39
DEM-6	1.33	5.59	2.23	1.8	3.4	0.54	0.51	0.64	0.58
DEM-7	0.49	3.05	1.24	1.00	1.00	0.19	0.5	0.31	0.69
DEM-8	0.39	3.52	0.8	0.79	0.79	0.22	0.29	0.32	0.12
DEM-9	0.32	2.39	0.89	0.51	0.77	0.14	0.27	0.18	0.19

Table 6. Morphometric parameters and time of concentration for the sub-basins of the DEM model.

variations can be derived from the errors in the initial map; both models were processed in ArcGIS 10.5, yet because they are different models and due to the errors mentioned above, there is a variation in the results.

Regarding the data provided by the Master Plan, the equivalent percentages of each of the results obtained by the different models in comparison to the Master Plan are presented in Figure 6. The light green colour represents the results of the GE (see label RGE in Figure 6) model and the dark green colour represents those of the DEM (see label RDEM in Figure 6), while the orange line indicates the 100% representing the reference values. The morphometric parameters to be evaluated are the area (A), perimeter (P), axial length (l), width of the basin (B), length of the main channel (lc), and slope of the basin (s). It can be observed that, on average, the basin model closest to the reference basin is that of the contour lines generated from Google Earth Pro (GE), at 98%. The DEM-derived basin model obtained is approximately 90%.

The peak flow rates obtained for each of the return periods, with each time of concentration, show that there are no significant deviations in the results from one to another. Observing the results of the flows for each of the models presented in the previous chapter, in the DEM model for each sub-basin, the highest flow values were obtained with the Kirpich equation. For the GE model, the highest flow values were obtained with the NRCS equation (TR-55). In the case of the Master Plan, there was no trend evident with any of the T_c equations.

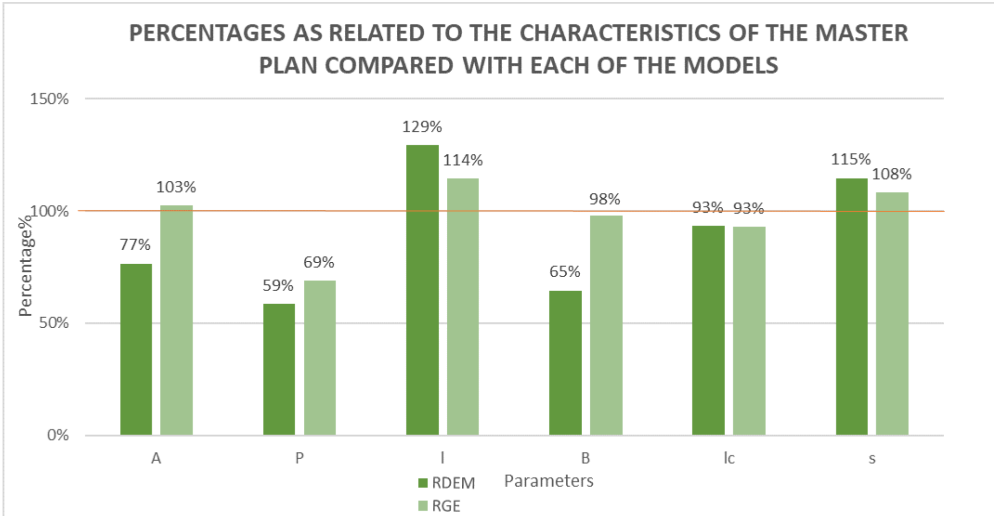


Figure 6. Comparison of the morphometric parameters of the models with the reference basin.

When analyzing the maximum water flow calculated for each model using the different equations of T_c (see Figure 7), the following can be observed:

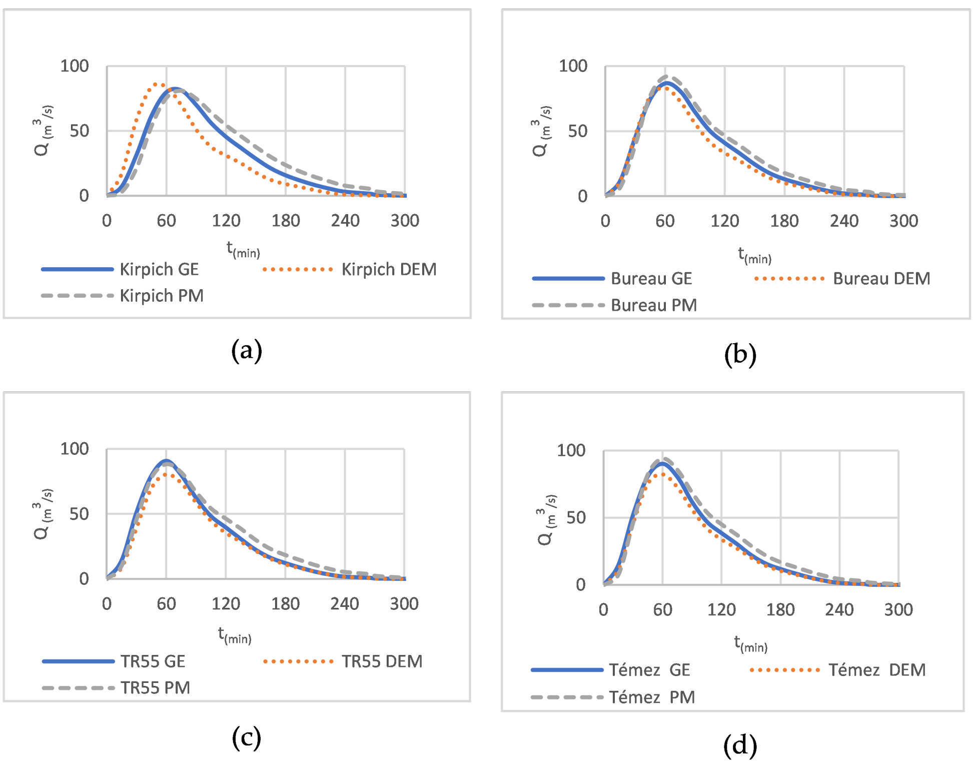


Figure 7. Flood hydrographs for a 5-year return period, with each T_c equation for each basin model resulting from each map type (GE, DEM and PM, Master Plan): (a) Hydrograph using the Kirpich T_c with each map type; (b) Hydrograph using Bureau's T_c with each map type; (c) Hydrograph using the NRCS (TR-55) T_c with each map type; (d) Hydrograph using Témez's T_c with each map type.

- Using the Kirpich equation (see Table 7), the DEM basin model has a higher peak flow value and a shorter time to peak compared to the other models at different times of concentration. The GE basin model and the Master Plan show similar behaviour in most of the return periods and the peak flow reached.

Map type	**Return period (years)**				
	5	**10**	**25**	**50**	**100**
GE	81.1	98.6	124.1	147.1	178
Master Plan	80.9	97.7	119.9	164.3	184.1
DEM	83.7	86.4	126.9	148.6	177.5

Table 7. Peak flow rates associated with different return periods (m^3/s), Kirpich T_c equation.

- Using the Bureau equation, the DEM basin model has the lowest values in the different return periods compared to the GE basin model and Master Plan (as shown in Table 8).

Map type	**Return period (years)**				
	5	**10**	**25**	**50**	**100**
GE	86.8	106.5	133.1	156.8	188.4
Master Plan	91.6	112.1	139.2	162.9	184.1
DEM	83	99.7	121.8	141	168.5

Table 8. Peak flow rates associated with different return periods (m^3/s), Bureau T_c equation.

- Using NRCS (TR-55) equation, the DEM basin model has the lowest flow values in the different return periods compared to the other models, which are more similar to each other (see Table 9). The time to peak for the basin in the different models using NRCS (TR-55) is the same, 60 minutes.

Map type	**Return period (years)**				
	5	**10**	**25**	**50**	**100**
GE	90.7	101.2	138.1	155	184.8
Master Plan	88.2	107.5	133.4	156	184.1
DEM	80.5	97.2	119.2	138.5	168.2

Table 9. Peak flow rates associated with different return periods (m^3/s), NRCS (TR-55) T_c equation.

- Using Témez's equation, the DEM model has the lowest values for peak flow rates for each return period, and the GE basin model and Master Plan share more similar values compared to the peak flow (see Table 10).

Thus, the basin model that best fits the flow rates obtained from the different T_c equations for the Master Plan is the GE model, taking into account the outflow of the basin. When analysing the data of the Master Plan model (reference basin) vs. the data of the GE and DEM models, we subsequently determine

Map type	**Return period (years)**				
	5	**10**	**25**	**50**	**100**
GE	90.3	110.3	137.3	164.2	193.1
Master Plan	93.9	114.1	141	164.4	192.9
DEM	82.2	98.7	120.6	139.7	165.2

Table 10. Peak flow rates associated with different return periods (m^3/s), Témez T_c equation.

the model that best fits the reference basin. This was carried out taking into account the coefficient of determination (R^2), as shown in Tables 11, 12, and 13.

Equation	**Return period (years)**				
	5	**10**	**25**	**50**	**100**
Kirpich	0.986	0.985	0.987	0.988	0.989
Bureau	0.988	0.987	0.988	0.990	0.992
Témez	0.987	0.988	0.990	0.988	0.985
TR-55	0.986	0.988	0.986	0.987	0.987

Table 11. Determination of R^2 of the GE model for return periods of 5, 10, 25, 50 and 100 years.

Equation	**Return period (years)**				
	5	**10**	**25**	**50**	**100**
Kirpich	0.981	0.980	0.983	0.985	0.986
Bureau	0.985	0.986	0.990	0.989	0.988
Témez	0.985	0.987	0.987	0.988	0.986
TR-55	0.984	0.987	0.990	0.991	0.992

Table 12. Determination of R^2 of the DEM model for return periods of 5, 10, 25, 50 and 100 years.

Equation	**Return period (years)**				
	5	**10**	**25**	**50**	**100**
Kirpich	0.973	0.966	0.953	0.946	0.946
Bureau	0.993	0.990	0.988	0.987	0.988
Témez	0.996	0.994	0.993	0.993	0.990

Table 13. Determination of R^2 of the Master Plan basin model for return periods of 5, 10, 25, 50 and 100 years.

- Both models have high goodness of fit; however, the model that best fit according to the reference line for the calculation of the peak flow rate obtained for the basin model of the Master Plan, taking into account the NRCS (TR-55) time of concentration was the GE model, as it presented highly significant goodness of fit values for all evaluated return periods.
- For the GE and DEM models, among the calculated flows, the one with the greatest impact is that obtained by the Bureau T_c and TR-55 T_c, respectively.
- For the basin model of the Master Plan, on average, the flows with fits as good as that obtained by NRCS (TR-55) are those obtained by the Témez equation.

- The results of the flows for the basin model of the Master Plan with each of the equations (Témez, Bureau, Kirpich) vs. the reference flow have highly significant goodness of fit (see Figure 8). This implies that the equations used can be applicable based on the reference and that the differences between the models studied are due to the variation of the morphometric parameters.

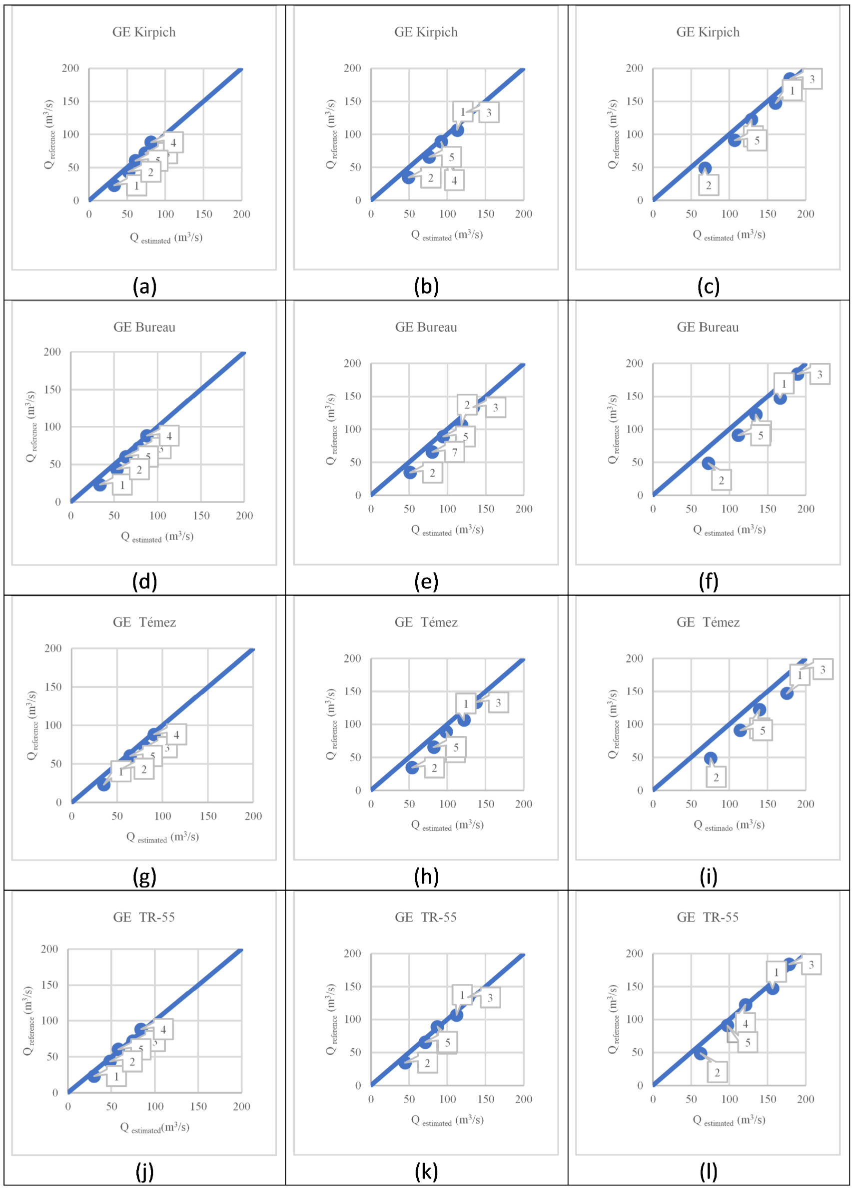


Figure 8. $Q_{estimated}$ vs. $Q_{reference}$ for return periods of 5, 25 and 100 years for the GE basin model: (a) Kirpich equation for a return period of 5 years; (b) Kirpich equation for a return period of 25 years; (c) Kirpich equation for a return period of 100 years; (d) Bureau equation for a return period of 5 years; (e) Bureau equation for a return period of 25 years; (f) Bureau equation for a return period of 100 years; (g) Teméz equation for a return period of 5 years; (h) Teméz equation for a return period of 25 years; (i) Teméz equation for a return period of 100 years; (j) Equation of TR-55 for a return period of 5 years; (k) Equation of NRCS (TR-55) for a return period of 25 years; and (i) Equation of TR-55 for a return period of 100 years.

4. Conclusions

From the basin delimitation process using different maps derived from a DEM, contour lines exported from Google Earth, and taking into account the reference data of the Master Plan of the city, we found a difference between the morphometric parameters obtained between each of them. Differences are due to the accuracy and management of each of the models. Each DEM contains an accuracy that depends on the area and the roughness of relief while the contour lines are derived from the starting map, and subsequently ArcGIS 10.5 also introduces errors in the system. These errors are unavoidable because these models are a simplification of reality and do not take into account any decisions made by engineers, such as the minimum elevation, which, since it is a basin that flows into a body of water that is at sea level, should be considered zero and not as shown by the programme (2 m.a.s.l.) to obtain flow rates more in line with their characteristics. Taking into account the outflow of the basin, when analysing the flow behaviour in each model, it was observed that the GE model and the Master Plan in each return period and with each T_c equation are similar, unlike the DEM model, which has higher or lower flow values compared to GE and Master Plan.

The comparison between a reference flow obtained through equation TR-55 for the data of the master plan against the flows obtained by the different equations that estimate T_c in each of the study models demonstrated the correlational behaviour between them. The statistical analysis allowed making a better selection of the basin and the time of concentration that best fits the reference model. Among the study models, the one with the best goodness fit compared to the reference was the GE basin, and the flows of best fit were those obtained by the Bureau equation.

Likewise, the variation in the morphometric parameters of each of the model, such as the slopes and lengths (axial length and length of the main channel), directly affects the equations used. The flows obtained from the model parameters using the different equations do not vary much because they depend largely on the same parameters, and the difference is due to the origin and construction of each equation. Thus, the flow rates obtained and their variability in the different models are directly related to the established area, the characteristics of the slopes, the flow travel and the rainfall event.

Funding: This research received no external funding.

Author contributions: Conceptualization, A. S-S. and Ó.E. C-H.; methodology, H. M. R. and D. A. P-V.; formal analysis, G.G.; writing—original draft preparation, A. S-S. and Ó.E. C-H.. All authors have read and agreed to the published version of the manuscript.

Disclosure statement: The authors declare no conflict of interest.

References

[1] Fernanda Julia Gaspari, Alfonso Martín Rodríguez Vagaría, Gabriela Elba Senisterra, Gerardo Andrés Denegri, María Isabel Delgado, and Sebastián Ignacio Besteiro. Caracterización morfométrica de la cuenca alta del río sauce grande, buenos aires, argentina. *Augm Domus*, 4:143–158, 2012.

[2] MR Vidal-Abarca, Carlos Montes, ML Suárez, and L Ramirez Diaz. Caracterización morfométrica de la cuenca del río segura: Estudio cuantitativo de las formas de las subcuencas. *Papeles de Geografía*, (12), 1987.

[3] Alejandra M Geraldi, M Piccolo, and Gerardo ME Perillo. Delimitación y estudio de cuencas hidrográficas con modelos hidrológicos. *Investigaciones Geográficas (Esp)*, (52):215–225, 2010.

[4] Adán Guillermo Ramírez García, Artemio Cruz León, Pastor Sánchez García, and Alejandro Ismael Monterroso Rivas. La caracterización morfométrica de la subcuenca del río moctezuma, sonora: ejemplo de aplicación de los sistemas de información geográfica. *Revista de Geografía Agrícola*, (55):27–43, 2015.

[5] Rofiat Bunmi Mudashiru, Ismail Abustan, and Fauzi Baharudin. Methods of estimating time of concentration: a case study of urban catchment of sungai kerayong, kuala lumpur. In *Proceedings of AICCE'19: Transforming the Nation for a Sustainable Tomorrow 4*, pages 119–161. Springer, 2020.

[6] Salvatore Grimaldi, Andrea Petroselli, Flavia Tauro, and Maurizio Porfiri. Time of concentration: a paradox in modern hydrology. *Hydrological Sciences Journal*, 57(2):217–228, 2012.

[7] Washington Ramiro Sandoval Erazo and Eduardo Patricio Aguilera Ortiz. Determinación de caudales en cuencas con poco información hidrológica. *Ciencia Unemi*, 7(12):100–110, 2014.

[8] T Bisantino, R Bingner, W Chouaib, F Gentile, and G Trisorio Liuzzi. Estimation of runoff, peak discharge and sediment load at the event scale in a medium-size mediterranean watershed using the annagnps model. *Land degradation & development*, 26(4):340–355, 2015.

[9] Helena M Ramos and Óscar E Coronado-Hernández. Iot, machine learning and photogrammetry in small hydropower towards energy and digital transition: potential energy and viability analyses. *Journal of Applied Research in Technology & Engineering*, 2023.

[10] Ockert J Gericke and Jeff C Smithers. Review of methods used to estimate catchment response time for the purpose of peak discharge estimation. *Hydrological sciences journal*, 59(11):1935–1971, 2014.

[11] Asghar Azizian. Uncertainty analysis of time of concentration equations based on first-order-analysis (foa) method. *American Journal of Engineering and Applied Sciences*, 11(1):327–341, 2018.

[12] Marzieh Mokarram and Majid Hojati. Comparis of digital elevation model (dem) and aerial photographs for drainage. *Modeling Earth Systems and Environment*, 1:1–6, 2015.

[13] Leilei Li, Jintao Yang, and Jin Wu. A method of watershed delineation for flat terrain using sentinel-2a imagery and dem: A case study of the taihu basin. *ISPRS International Journal of Geo-Information*, 8(12):528, 2019.

[14] Zhengqing Lai, Shuo Li, Guonian Lv, Zhirong Pan, and Guosong Fei. Watershed delineation using hydrographic features and a dem in plain river network region. *Hydrological Processes*, 30(2):276–288, 2016.

[15] Marvin E Quesada and Matt Marsik. Uso de modelos de elevación digital como alternativa para mostrar errores en mapas topográficos. *Revista Geográfica de América Central*, 1(48):77–93, 2012.

[16] AB Ariza-Villaverde, FJ Jiménez-Hornero, and E Gutiérrez De Ravé. Influence of dem resolution on drainage network extraction: A multifractal analysis. *Geomorphology*, 241:243–254, 2015.

[17] D. Jiménez. Inundaciones en cartagena: sin soluciones definitivas ni parciales. http://moir.org.co/Inundaciones-en-Cartagena-sin.html [Accessed: June 14, 2016].

[18] Jorge Iván Pérez Alvarino et al. Análisis hidráulico del canal ricaurte como parte del drenaje de aguas lluvias en cartagena de indias mediante la implementación del programa hec-ras 4.1. *Título el especialista en recursos hídricos. Universidad de los Andes Departamento de Ingeniería Civil y Ambiental Centro de Investigaciones en Acueductos y Alcantarillados, – CIACUA.*, 2016.

[19] ZP Kirpich. Time of concentration of small agricultural watersheds. *Civil engineering*, 10(6):362, 1940.

[20] Isabel Kaufmann De Almeida, Aleska Kaufmann Almeida, Jamil Alexandre Ayach Anache, Jorge Luiz Steffen, and Teodorico Alves Sobrinho. Estimation on time of concentration of overland flow in watersheds: a review. *Geosciences= Geociências*, 33(4):661–671, 2014.

[21] Roger Cronshey. *Urban hydrology for small watersheds. Time of concentration and travel*. Number 55. US Department of Agriculture, Soil Conservation Service, Engineering Division, 2nd edition, 1986. pages 29–33.

[22] POT (2001). Decreto no 0977 de 2001. http://curaduria2cartagena.com/pdf/POT.pdf [Accessed: March 23, 2021].

[23] Alvaro Gonzalez-Alvarez, Oscar E Coronado-Hernández, Vicente S Fuertes-Miquel, and Helena M Ramos. Effect of the non-stationarity of rainfall events on the design of hydraulic structures for runoff management and its applications to a case study at gordo creek watershed in cartagena de indias, colombia. *Fluids*, 3(2):27, 2018.

[24] Alcaldía Mayor de Cartagena de Indias. Estudios y diseños del plan maestro de drenajes pluviales del distrito de cartagena de indias. https://www.yumpu.com/es/document/view/42121178/plan-maestro-de-drenajes-pluviales-cartagena-parte-1 [Accessed: September 24, 2019].

[25] Departamento Administrativo de Valorización Distrital. Estudios y diseños del plan maestro de drenajes pluviales del distrito de cartagena de indias, 2008.