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Computation of Time of Concentration Based on Two-Dimensional Hydraulic Simulation

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Abstract: Time of concentration (TC) is a parameter in runoff estimation, used to study and design different types of projects in watersheds. Any error in TC calculation leads to an inaccurate estimation of the design flow, which can lead to over-sizing or under-sizing of designed facilities that can have great economic and environmental consequences. Therefore, choosing the correct method to estimate TC is of great importance. Due to the diversity of estimation methods in the literature, the obtained TC values are different. This study aims to present a new method to calculate TC, based on its main concept, i.e., the time required for a water parcel to reach its outlet from the farthest hydrological point of a watershed. A two-dimensional hydraulic simulation was used to model the water parcel travel. A watershed was selected as a case study, and its time of concentration was determined by salt solution tracing. The field measurement results were used for calibration of the numerical simulation model. Meanwhile, 31 empirical relations in the literature were reviewed to determine the most accurate ones. Estimated TC values were compared with the measured ones, and the relative error percentage was used to evaluate the accuracy of the result. In the empirical TC methods, the maximum error was above 300%, and the minimum error was 6.7% for the field studied area. The relative errors of hydraulic simulation outputs were between 3 and 27%. The results showed that only three empirical methods, namely Simas and Hawkins, SCS_{lag}, and Yen and Chow, had the least errors respectively equal to 6.7%, 8.660%, and 13.5%, which can be recommended for the studied area and those with similar hydrological characteristics. On the other hand, hydraulic simulation is also introduced as an efficient method to determine TC which can be used in any desired watershed.

Keywords: runoff; salt solution tracing; empirical formulas; case study; sensitivity analysis

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1. Introduction

Time responses are fundamental parameters for hydrologists to design floods. The number of precipitations may not cause flood risk; however, the runoff distribution may. As a result, the design of flood requires time responses of watersheds [1,2]. Based on Wong [3], the time of concentration (TC) is the most frequently used time parameter. Proper estimation of TC leads to accurate design of flood control structures, preparation of flood hazard maps, and facilitates local authorities for making decisions before floods and it is of great importance. Time of concentration (TC) is the time for a water parcel to travel from the watershed divide to its outlet along the longest watercourse [4]. Time of concentration is necessary to estimate discharge rate and volume, generate runoff hydrographs for application in drainage projects, design spillways and other hydraulic structures, development of flood predicting models and flood alert systems, and much other hydrological analysis and water resources management studies/projects. Therefore, accurate estimation of TC is crucial in the management of watersheds since the most severe floods are those caused by rainfalls with durations equal to or greater than the TC of a watershed.

Three main techniques can be found in the literature to measure or estimate TC including physical, graphical, and analytical methods. In physical methods, direct measurement of TC is applied using chemical solution traces [5]. The graphical approaches consider rainfall hyetographs and flood hydrographs which require data that are not usually available in many watersheds. Analytical methods include empirical equations which determine TC based on watershed characteristics. Each relation is developed for specific conditions and works in a special area in the world, those that have the same physical parameters [6]. That is why various TC estimation methods can bring differences of up to 500% [7]. Such differences are arisen from ignoring the flow path conditions such as bed roughness, topography, vegetation cover, and hydraulic radius at various sections. Empirical TC formulas have been developed through regression relation against watershed physical characteristics in different parts of the world. Such formulas may not be suitable from the climatic and hydrological standpoint for many other areas, and this is the reason that empirical equations are site-specific and it is hard to decide their accuracy for an area of interest. Many researchers have focused on evaluating different empirical relations in the prediction of TC. Ravazzani et al. [8] used 24 frequent empirical equations to estimate the time of concentration in the northern part of Italy. The studied zone consists of 46 catchments and each of which covers different areas ranging from 56 to 1588 km^2. Among empirical methods, Bransby-Williams, Giandotti, SCS, Témez, and Ferro equations rendered the best estimation of TC. Soroush and Eslamian [9] conducted research to find the best TC relationship in Karun and Dez rivers basin in Iran. They investigated different formulas such as Kirpich, Espey, Ventura, Passani, Carter, Johnstone-Cross, and Pilgrim-McDermat and then compared them with the TC obtained from the analysis of watershed hydrographs. The results revealed that Passini and the Carter formulas indicated maximum and minimum least error in calculating TC in the studied watersheds, respectively. McCuen et al. [10], employed eleven TC formulas for 48 urban basins and concluded that the method of calculating the average velocity in the channel, presented by the Natural Resources Conservation Service (NRCS) indicates the least error. Pilgrim [11] examined 96 watersheds in the South Australian region and proposed an equation that uses only the watershed area to estimate TC. Goitom [12] studied the TC in one of Arizona's watersheds and showed that the Kirpich equation can be a suitable formula. In a study in Texas, Fang et al. [13] used five empirical equations to estimate TC in 96 watersheds in Texas of which 49 cover an area less than 25 km^2. They applied an automated method (using DEM and GIS) and a manual method (with and without watershed delineation) to estimate TC as well. They concluded that using automated and manual techniques are similar with relative differences between 6.4 to 16.9% in predicting. In addition, Kirpich and Haktanir-Sezen formulas yield reliable TC estimations. Eslamian and Mohebbi [14] used SAS software to evaluate 14 empirical TC estimation equations in the watersheds of Tehran, Mazandaran, and Isfahan provinces, using SAS software. The results indicated that the Pilgrim-McDermott equation was more accurate than the other methods. Dastourani et al., [15] compared the estimated TC values with the field observations to evaluate the efficiency of six empirical equations for Mashmad and Dehbala watersheds in Yazd province and suggested Haktanir–Sezenand California, as the best equation. González-Álvarez et al. [16] applied ten equations and two TC methodologies to calculate TC in fifteen catchments. They stated that none of the equations can render a reliable estimation of TC, however, in case there is no rainfall-runoff data in the area, the NRCS method considering its own limitations, can render reliable estimations. Bennis and Crobeddu [17] used a model to reproduce runoff based on an improved rational hydrograph (considering "the capacity to use variable intensity rainfalls and an alternative to the lumped runoff coefficient by introducing infiltration for pervious areas and initial abstraction for impervious areas") to simulate runoff. The model considers pervious and impervious areas, changing in rainfall time, and initial losses. They compared simulation results with measured runoff events from two catchments which cover an area of 23.3 and 177 ha and concluded that there is a good agreement between reproduced and measured runoff hydrograph. Sadatinejad et al., [18] using hydrometric data in six sub-watersheds of Karun River in southwestern Iran, developed a relationship called the Shahrekord model, which uses watershed perimeter and the length of the main canal to estimate the TC.

Due to the high data demand and experimental nature of TC calculating models, the estimation accuracy of each model can vary depending on the degree of similarity of the study site to the original location of that model; especially because the assessment of the field data is either difficult or based on various methodologies. In such cases, the lower the sensitivity of each model to the input variables, the more comprehensive it will be for use in basins with different physiography or in conditions where it is not possible to accurately measure the input parameters. Therefore, in comparison with different TC models, a criterion for selecting the better model is its lower sensitivity to the input data, provided that other comparative indicators are also acceptable.

A review of previous studies indicates that a large number of studies have focused on validating different methods to estimate TC based on watershed data. The results are generally valid for those regions or similar areas. Yet, as reported by Grimaldi et al., [7], when using the empirical equation, variations up to 500% are expected.

But a question still remains: which formula should be applied in the absence of a flow hydrograph and the corresponding rainfall hyetographs, which are not commonly available in most watersheds? The current study aims to answer this question using the classical definition of TC; that is, the time required for a water parcel/drop to flow along the longest flow course in any desired watershed. To do this, the two-dimensional HEC-RAS 5.0.7 model was used for a hydraulic simulation of the flow. The 2D simulation was selected because it was a novel approach among TC computation methods. In addition, 2D simulation yields more realistic results than 1D methods since the topographic variations in 1D models resembles cross sections (points along a straight line). These cross sections are usually at great distances and ignore topographic variations. However, in a two-dimensional simulation, topographic points created from DEM have smaller spacing (higher spatial resolution), causing the bathymetry to be built as a plane. In addition to this, the factors that had the greatest impact on TC estimation were considered in the 2D simulation, including roughness, flow length, topography, and river slope. Currently, there is a wide range of empirical relations available in the literature. Each has been developed based on specific physical and hydrologic conditions, whereas 2D hydraulic simulation proposes a method independent of these factors which can be used in every desired watershed and avoid confusion associated with selecting empirical relations.

In addition, 31 different empirical equations were also used to estimate the TC, and the sensitivity analysis was carried out to identify the least sensitive formulae to find a range of acceptable TC values to be compared to 2D simulation and measured data. Salt solution tracing was applied to estimate the watershed's time of concentration and validate the answers in a watershed near Shiraz City, Iran. To the best knowledge of the authors, two-dimensional hydraulic simulations have never been considered as a method to estimate TC.

2. Methodology

2.1. Study Area

The study area which covers an area of 3.529 km^2 is the Aliabad watershed located to the west of Shiraz City, Iran (29°43′–25°10′ N; 52°18′–29°30′ E). The Aliabad River flows in this area as a seasonal river. During the wet period–November to June-runoff comes from precipitations and water level-stream flows into the river; In the dry season- July to November-there is little flow in the river. Therefore, it is classified as an intermittent river. The river reach joins the Dare-Marun and Pasukohak reaches and finally flows into the Khoshk River of Shiraz. Figure 1 shows the border of the watershed with its main tributaries.

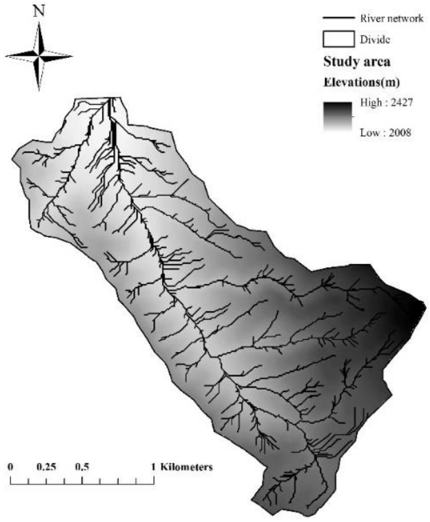

Figure 1. Borders of the study area with its main tributaries.

DEM files with a spatial resolution of 12.5 m (from Advanced Land Observation Satellite (ALOS)) and other required data such as rainfall records, temperature, evaporation, and curve number (CN) values, were provided from the local Natural Resources Organization. The precipitation data were measured using the closest rainfall station. The average annual precipitation is about 524 mm. The average maximum temperature ranges from 19.6 to 22.9, and the minimum ranges from 5.2 to 6.7 degrees Celsius. The temperature data are obtained from an evaporation station located next to the watershed. The annual evaporation is 2415 mm ranging from 2264 to 2528 mm. Based on the Koppen classification, the regional climate is categorized as Bsk (semi-arid or steppe climate with an average annual temperature of fewer than 18 degrees Celsius, where evaporation is much greater than precipitation).

To determine Curve Number (CN), the organization gathers this information including aerial photographs, topographic maps, watershed characteristics (physiography, meteorology, geology, geomorphology, vegetation, land use), and prepares the resulting image by assembling geological maps. Then, field observation is completed to distinguish land units based on soil characteristics and water samples. Finally, some profiles are drilled by personnel and the soil samples are sent to the laboratory for physicochemical analysis and determining soil features, patterns, and structures.

Using the above information, the soil hydrological group is determined based on SCS classification.

Field surveys, along with an inspection of the available DEM and national surveying organization maps, were conducted to determine the watershed divide. Watershed physical features are indicated in Table 1.

The maximum annual rainfall values of the catchment were analyzed to obtain 24 h rainfall with a 2-year return period which was equal to 52.34 mm per hour (mm/h). The time of concentration was calculated by the salt solution tracing method [19]. In order to measure the travel time of the salt solution and in order to find sufficient salt concentration for the 500-m range length, some trial-and-error procedures were performed. Moreover, to enhance the accuracy of the measurements and reduce the environmental side effects of the dissipation of the salt solution along the river, the length of the main river was divided into six reaches (500-m range length) and the measurements were made for each separately to determine adequate centration of salt solution. Adequate concentration means required centration to be identified by the EC (Electrical Conductivity) meter located downstream of the reach with Micro Siemens per centimeter (µs/cm) accuracy. This concentration was found to be 326 g per liter (gr/l) for the selected reach length. After pouring the salt solution into the stream, the timer was set to run. Simultaneously someone positioned 500m downstream of the injection point collected water samples in a cap continuously, while the timer was recording the EC against time intervals. The time interval between the start time of the salt solution injection into the reach and the arrival of the peak was considered the travel time.

Table 1. Physical parameters of Aliabad watershed.

Parameter	Value	Unit
Differences in main river elevation	273	m
Watershed length	3323.2	m
Watershed width	1859.2	m
mean elevation	2217.5	m
area	3.53	km^2
Main river average slope	0.07	m/m
Watershed average slope	0.298	m/m
Equivalent circle diameter	2120.14	m
CN	76.41	-

Such measurements were repeated along the river in successive intervals to the outlet to obtain the total travel time as a sum of successive interval outputs. The measurements were repeated on different dates and one was selected in initially wet conditions of soil to minimize infiltration effects as much as possible. Besides the measurement were started as close as possible to the basin's border to minimize the overland flow duration.

2.2. Empirical Formulas

Thirty-one empirical formulas were selected to estimate the TC for the Aliabad watershed. Such estimated values were then compared with the observed values. The formulas were carefully selected to be as consistent as possible with the information and data available from the watershed. The selected formulas, along with their necessary explanations and references, are listed in Tables 2–6.

Table 2. TC (h) and RE (%) for methods based on L, L_t, S_r, and A (category I).

Equation Name and References	Formula	Description	Estimated TC (h)		RE (%)	
			Estimated by Empirical Method	**2D Simulation (Average of Two Estimations)**	**Equations**	**2D Simulation**
Haktanir and Sezen, [6,20]	$TC = 0.7473L^{0.841}$	Derived from 10 basins in Turkey, $11 < A < 9867$ km^2	2.132	(1.8 + 2.22/2) = 2.01	22.124	14.85
Temez, [21]	$TC = 0.3L^{0.76}S_r{}^{-0.19}$	For Spain natural watersheds	1.303		25.347	
Bransby –William, [8,21]	$TC = 0.605\frac{L}{(100S_r)^{0.2}A^{0.1}}$	Rural watersheds, $A < 129.5$ km^2	1.284		26.440	
Pilgrim and McDermott, [8,21]	$TC = 0.76A^{0.38}$	$0.1 < A < 250$ km^2	1.227		29.716	
Pasini, [21]	$TC = 0.108A^{0.333}L^{0.333}S_r{}^{-0.5}$	Italian rural watersheds	0.948		45.729	
US Army Corps of Engineers, [8]	$TC = 0.3788(1.1 - C)L^{0.5}S_r{}^{-0.333}$	$A < 0.5$ km^2	0.83		52.471	
Picking, [21]	$TC = 0.0883L^{0.667}S_r{}^{-0.333}$	Rural watersheds	0.499		71.436	
Kirpich -Tennessee, [22]	$TC = 0.000325L^{0.77}S_r{}^{-0.385}$	4 < A < 50 ha, S: 3 < < 10%	0.490		71.912	
California Curvets Practice (CHPW), [21]	$TC = 0.95\left(\frac{L^3}{H_o}\right)^{0.385}$	For small mountainous US watersheds	0.474		72.846	
Johnston and Cross, [7]	$TC = 300\left(\frac{L}{S_r}\right)^{0.5}$	$64 < A < 4200$ km^2	0.387		77.840	
Van Sickle, [10]	$TC = 0.009167L_t{}^{0.13}L^{0.13}S_r{}^{-0.065}$	A < 36 sq mile	0.229		86.897	
Kirpich -Pennsylvania, [21]	$TC = 0.01104L^{0.77}S_r{}^{-0.5}$	$0.004 < A < 0.453$ km^2, $0.03 < < -0.1$	0.111		93.655	
Chow, [8,20]	$T_c = 0.1602L^{0.64}\ S_r{}^{-0.32}$	$0.01 < A < 18.5$ km^2, $0.0051 < < 0.09$ m/m	0.809		53.7	
Flavell, [21]	$TC = 2.31A^{0.54}$	$0.1 < A < 250$ km^2	4.564		161.379	
Carter, [10]	$TC = 1.7L^{0.6}S_r{}^{-0.3}$	A < 8 sq mile, L < 8 miles, S_r= 0.5%	6.073		247.843	
Sheridan, [21]	$TC = 2.20L^{0.92}$	$2.62 < A < 364.34$ km^2	7.064		304.606	

Note: L: main river length (km), S_r: river slope (m/m), A: watershed area (km^2), C: runoff coefficient from rational method, H_o: quota difference between the end of the main channel (m), Lt: sum of the total drain ways (mi).

Table 3. *TC* (h) and RE (%) for methods based on S_r, C, CN and D (category II).

Equation Name	Formula	Description	TC (h)		RE (%)	
			Estimated by Empirical Method	2D Simulation (Average of Two Estimations)	Equations	2D Simulation
Simas and Hawkins, [21]	$TC = 0.322\mathrm{A}^{0.594}L^{-0.594}{S_r}^{-0.15}{S_{SCS}}^{0.312}$	0.001 < A < 14 km^2	1.863	(1.8 + 2.22/2) = 2.01	6.722	14.85
SCS$_{\text{lag}}$, [23]	$TC = 1.67\frac{L^{0.8}(S+1)^{0.7}}{1900{S_r}^{0.5}}$	A < 8 km^2	1.592		8.660	
Williams, [6]	$TC = \frac{0.272L\mathrm{A}^{0.4}}{D{S_r}^{0.2}}$	India Watersheds, A < 129.5 km^2	1.285		26.398	
TXDOT, [24,25]	$TC = 0.702(1.1 - C)L^{0.5}{S_r}^{-0.333}$	A < 0.8 km^2	0.752		56.956	

Note: L: Main river length (km), A: Watershed area (km^2), S_r: river slope (m/m): *Sscs*: Surface storage (mm), *S*: Maximum potential retention (in), *D*: Equivalent diameter of watershed (km), *C*: rational method runoff coefficient.

Table 4. *TC* (h) and RE (%) for methods based on P$_{24}$ (category III).

Equation Name	Formula	Description	Estimated TC (h)		RE (%)	
			Estimated by Empirical Method	2D Simulation (Average of Two Estimations)	Equations	2D Simulation
Kadoya and Fukushima, [26,27]	$TC = \frac{1}{60}C_T\mathrm{A}^{0.22}i^{-0.35}$	km^2 < 143 A < 0.5	1.321	(1.8 + 2.22/2) = 2.01	24.335	14.85
Morgali and Linsley, [26–28]	$TC = 0.12\frac{n^{0.6}L^{0.6}}{{S_r}^{0.3}}i^{-0.4}$	small catchment, urban areas, A < 10 to 12 ha	1.149		34.169	
Arizona DOT, [21]	$TC = 0.0097956\mathrm{A}^{0.1}(1000L)^{0.25}L_{\text{ca}}^{0.25}{S_r}^{-0.2}$	Agricultural watersheds	0.948		45.707	
US Army, [26,27]	$TC = \left(\frac{1}{60}\right)\left(10.57 + \frac{0.12}{S_r}\right)\left(\frac{L}{30.48}\right)^{0.55-\left(\frac{0.001}{S_r}\right)} * i^{-0.43}$	Derived from concrete trough, A = 500 ft, S = 0.5, 1 and 2 %	0.478		72.634	

Note: A: Watershed area (km^2), *CT*: Storage coefficient (190–290 mm), *i*: maximum rainfall intensity with 24 h duration and 2-year return period (mm/h), *L*: Main river length (km), S_r: river slope (m/m), n: manning roughness coefficient, *L*ca: mean length starting from the concentration spot along the *L* up to the spot where *L* is perpendicular to the centroid of the catchment (m).

Table 5. *TC* (h) and RE (%) for methods based on Elevation (category IV).

Equation Name	Formula	Description	Estimated TC (h)		RE (%)	
			Estimated by Empirical Method	2D Simulation (Average of two Estimations)	Equations	2D Simulation
Bransby–William, [8,21]	$TC = 0.605\frac{L}{(100S_r)^{0.2}A^{0.1}}$	Rural watersheds, A < 129.5 km^2	1.262	(1.8 + 2.22/2) = 2.01	27.708	14.85
Ventura, [8,21]	$TC = 4A^{0.5}L^{0.5}H^{-0.5}$	rural watersheds, A < 10 km^2	0.857		50.899	
Pickerin, [21]	$TC = 0.9482L^{1.155}H_o{}^{-0.385}$	Equivalent to Kirpich	0.473		72.898	
Basso, [21]	$TC = 0.957L^{1.155}H^{-0.385}$	Wave equation and green-ampt infiltration method	0.213		27.708	

Note: L: Watershed length (km), A: Watershed area (km^2), S_r: river slope (m/m), H: Main river elevation differences (m), H_o: quota difference between the ends of the main channel (m).

Table 6. *TC* (h) and RE (%) for methods based on n (category V).

Equation Name	Formula	Description	Estimated TC (h)		RE (%)	
			Estimated by Empirical method	2D Simulation (Average of Two Estimations)	Equations	2D Simulation
Yen and Chow's, [29]	$TC = 1.2n^{0.6}L^{0.6}S_r{}^{-0.6}$	overland flow, A < 50 km^2	1.510	(1.8 + 2.22/2) = 2.01	13.515	14.85
NRCS, [7,8]	$TC = 0.0526\left(\frac{1000}{CN}-9\right)^{0.7}L^{0.8}S_r{}^{-0.5}$	Small rural basins, sA < 8 km^2	1.435		17.818	
Hathaway, [21,30]	$TC = 0.6061N^{0.47}L^{0.47}S_r{}^{-0.235}$	Analysis of overland flow, L < 0.37 km, A < 10 ha	1.067		38.882	

Note: L: Main river length (km), S_r: Main river average slope (m/m), n: Manning coefficient, CN: Curve Number, N: retandness.

2.3. Hydraulic Simulation

Two-dimensional HEC-RAS version 5.0.7 was used to perform the two-dimensional hydraulic simulation. This model was developed by the US Army Corps of Engineers Hydrologic Engineering Center. HEC-RAS uses two sets of main equations to model unsteady flow conditions: continuity and momentum (in x and y directions) equations. The model employs an implicit finite volume method to solve governing equations for the unsteady flow. The implicit finite method enables modelers to use larger computational time steps and improve stability. In the simulation, the flow can pass through a completely dry area, and the model can also account for the rapid influx of water into the region. Thus, HEC-RAS can handle supercritical, subcritical, and a mix of both of the two.

The model uses the details of the underlying terrain to develop the geometry. That is to say, to represent the underlying terrain, the software uses both structured and unstructured cells including triangle, square, and five- or six-sided elements that do not require a flat bottom. Thus, each computational cell is based on the details of the underlying terrain, called the "high-resolution subgrid model" [31].

To stabilize the model, selecting the appropriate time step is crucial. Selecting the appropriate time step is a function of both cell size and the velocity of flow passing through cells. As a result, we used the trial-and-error method considering the following relation:

$$c = \frac{V\Delta T}{\Delta x} \leq 2 \text{ with the max } C = 5$$

In which C is Courant Number and V is the wave velocity, ΔT is the time step and Δx is cell size. After determining cell size in early steps, users try different time steps to gain stable results. Fortunately, HEC-RAS 5 has an option that enables the user to select a desired bound for the Courant number in which the model picks the best time step in each cell to stabilize the simulation. This option decreases the instability issues and accelerates the required time for running the model. Accordingly, the Courant number is bounded between 0.5 to 4. It confirms that estimation is not affected by both cell size and time steps. In addition, HEC-RAS has a preprocessor for improved stability, calculating cells based on the hydraulic condition of the underlying terrain. In other words, the model computes the elevation-volume relationship and then the dry cell is wetted with accurate water volume in each cell. Each cell is evaluated as a cross-section based on hydraulic details (roughness, area, and wetted perimeter). Therefore, modelers can use not only large computational cells but also the flow features, based on the conditions of the underlying governing terrain.

In HEC-RAS, the time of concentration is calculated based on flow velocity, so that by solving the governing equations and applying underlying terrain conditions, the model simulates the flow in the river, entraining the water parcel from the upstream (Headwater) to the watershed outlet. Then, the time interval that takes the water to move from the headwater to the outlet is recorded as the time of concentration.

Assuming an incompressible flow, the differential form of the governing equations are as follows:

Continuity equation:

$$\frac{\partial H}{\partial t} + \frac{\partial (p)}{\partial x} + \frac{\partial (q)}{\partial y} = 0 \tag{1}$$

Momentum equation in the x direction

$$\frac{\partial p}{\partial t} + \frac{\partial (p^2 H)}{\partial x} + \frac{\partial (g\frac{H^2}{2})}{\partial x} + \frac{\partial (pq/H)}{\partial y} = gH(\frac{-\partial h_0}{\partial x} - \frac{p\sqrt{p^2+q^2}}{C^2H^2}) + v[2\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 q}{\partial x \partial y}] \tag{2}$$

Momentum equation in the y direction

$$\frac{\partial q}{\partial t} + \frac{\partial (q^2 H)}{\partial y} + \frac{\partial (g\frac{H^2}{2})}{\partial y} + \frac{\partial (pq/H)}{\partial x} = gH(\frac{-\partial h_0}{\partial y} - \frac{q\sqrt{p^2+q^2}}{C^2H^2}) + v[2\frac{\partial^2 q}{\partial y^2} + \frac{\partial^2 q}{\partial x^2} + \frac{\partial^2 p}{\partial x \partial y}] \tag{3}$$

where H is the total water depth, h_0 is the water surface elevation, p and q are the flux per unit length in x and y directions respectively, g is the acceleration due to gravity, C is the Chezy friction coefficient, and ν is eddy viscosity.

To find the most leading parameters in TC estimations, sensitivity analysis was considered as a criterion of evaluation. The aim of such an analysis is to detect TC changes due to variations in effective watershed variables. Most sensitivity studies in the literature define a coefficient and/or figure representing the changes in model output against changes in model input, which might be problematic when comparing inputs due to differences in dimensions and units [32]. This problem can be resolved by correlating the relative changes of the dependent variable to those of the independent one [33]. The main methods of sensitivity analysis are the "sensitivity curve" and "sensitivity coefficient" [34]. A sensitivity curve is a plot indicating the correlation between relative changes of the dependent and independent variables, of which the linearity and slope signify the level of sensitivity [35]. "Sensitive coefficient" was defined as the ratio of the change rate of TC and the change rate of climate variable [36,37]. Compared with the graphical approach, the sensitivity coefficient approach is more convenient and precise [38]. Negative/positive sensitivity coefficients, respectively point out inverse/direct relationships between the dependent and independent variables, while the absolute value of sensitivity coefficients reflects the degree of TC sensibility from a given variable. For the TC estimation model, due to the multivariate nature of the model, it is more complicated to compare sensitivity through partial derivatives, where each variable (Vi) has its specific dimension and value range. By using the dimensionless relative sensitivity coefficient (S_{Vi}) introduced by McCuen [37], this study overcomes such problems as follows:

$$S_{V_i} = \lim_{\Delta V_i \to 0} \left(\frac{\Delta T_c / T_c}{\Delta V_i / V_i} \right) = \frac{\partial T_c}{\partial V_i} \cdot \frac{V_i}{T_c} \tag{4}$$

3. Results and Discussions

3.1. Empirical Relations

Due to the multiplicity of the empirical relations studied, TC models are classified into five categories, according to the distinctive factors in their formulas. These five categories include: models based on watershed area and the main river length and slope (category I), models based on equivalent diameter, watershed slope, and infiltration/runoff coefficients (II), models including 24-h precipitation (III), elevation-based models (IV) and models consisting of Manning's roughness coefficient (V). Obviously, some parameters such as river length and slope are involved in many models, and the basis of such classification is those unique parameters distinguishing different models.

The relations were evaluated by comparing the calculated TC values with the field measured concentration time of 1.75 h as a reference. Percentage of Relative Error (RE%) as a statistical index was used to compare the accuracy of the method, the results of which are presented in Tables 2–6. The Percentage of Relative Error (RE%) can be described as follows:

$$RE = \frac{|Pi - Oi|}{Oi} * 100 \tag{5}$$

in which, Oi and Pi are the observed and predicted values, respectively. In category I, Haktanir and Sezen [39] yield the best results among others. Haktanir and Sezen [39] developed synthetic unit hydrographs for ten different watersheds in Turkey by means of the probability density function. A regression equation was developed for peak discharge and lag time of the mentioned unit hydrographs. Haktanir and Sezen [39] claimed that they selected ten basins based on reliable measured data. Basins apparently differ in runoff characteristics with a wide range of sudden and late peaking hydrographs. Therefore, the equation can be applied for watersheds with different climatic characteristics including runoff, area, and length. Besides, Fang et al. [13] showed that this equation produces reliable estimations for TC. This explains why this equation resulted in the best estimation in category I. In the same category, Sheridan yields the worst results, since Sheridan focused his study on flatland basins and developed an equation in which TC is only dependent on the main river length. Our study area is a mountainous watershed completely different from those studied by Sheridan. Therefore, this method yields the lowest accuracy among others in category I.

Simas and Hawkins relation gives the best result among category II relations as well as other categories. Simas and Hawking [40] developed an equation from a comprehensive study of 5000 rainfall-runoff events in 168 watersheds in the United States, with input data ranging from 0.001 to 14 km^2. In addition, four different parameters are taken into account in this relation. These parameters include watershed area, average slope, length, the main river, and surface storage. The wide range of input data and various parameters included in this relation justifies the high accuracy of this method. In the same category, the SCS lag equation yields the best result after Simas and Hawking. This equation was developed by studying twenty-four rural basins with drainage areas less than 8 km^2, which matches the present study condition. SCS lag method was developed by Mockus [23]. This relation includes a wide range of conditions from densely forested to steep watersheds and smooth pared areas to meadows. In addition, in this method, the curve number which indicates the infiltration properties of the watershed are also taken into consideration. This explains the accuracy of this method. This method has been introduced as the second accurate experimental relation. In the same category (Table 3), TXDOT yielded the highest RE. This equation is the modification of FAA's method, which is appropriate for areas less than 0.8 km^2, which is smaller than the study area in the current research. Thus, this is the main reason why this relationship cannot produce suitable results. To sum up, as Salimi et al. [24] stated, the coverage area is one of the most important parameters in TC estimation.

Kadoya and Fukushima give the best result among the third category relations. This equation was developed for a wide range of watershed areas from 0.5 to 13 km^2. TC is derived based on a physically based model tested in natural watersheds. This can explain the acceptable result of this equation. US Army equation was derived by conducting experiments in three concrete pans with 500 feet in length and a slope of 0.5 to 2%. Rainfall simulations were used to produce rainfall over the entire surface. Roughness was also generated artificially by placing different materials such as metal plates. An artificial flow path initially developed from airfield drainage data can explain the 72% relative error of this relation.

According to Table 5 (category IV), Bransby-Williams yielded the best TC estimation, considering relative error. This is because the Bransby-Williams's equation is recommended for watersheds with areas less than 130 km^2, such as the one in the present study. In addition, the equation yields an appropriate estimation for remote local surface drainage with the natural terrain, which is consistent with this study's watershed characteristics. California Calvert Practice yielded a large relative error in the same category. This is because of the area coverage, which is to say, this equation yields an appropriate estimation for small areas ranging from 0.4 to 45.3 ha, which is not comparable with the studied area in this research (352.9 ha).

As specified in Table 6 (category V), Yen and Chow, and Hathaway resulted in the minimum and maximum relative errors, respectively. Yen and Chow equations are recommended for small watersheds with an area less than 50 km^2 [29], which can be used for the present study area. For the Hathaway equation (RE = 38.88%), it should be mentioned that this equation was developed for small watersheds less than 4 ha, with a slope of less than 1% with the main river length of $L < 0.37$ km [28,41]. It is obvious that none of the above criteria is consistent with the characteristics of the watershed of the present study. Therefore, that is why the Hathaway equation is not suitable for watersheds such as Aliabad.

The minimum residual value is 0.12 for Simas and Hawkins formula, which belongs to category (II) as well as the least average residual values, which include L, L_t, S_r, and A parameters. Moreover, this category contains more relations compared with other ones. It can be inferred that these parameters are the most distinctive factors in the calculation of TC. It is worth noting that most of these parameters are considered in the two-dimensional simulation. The river length is directly obtained from DEM and introduced to the numerical model as the flow path. While empirical formulas take an average slope into account, the slope is more accurately considered in the numerical simulation. Further, other important factors, such as Manning's roughness coefficient, are also included in the numerical simulation. The results of the two-dimensional model will be discussed later.

Only four methods (12.5% of the total empirical methods) indicated relative errors of less than 20%. In Yen and Chow method, the resistance factor or Manning's roughness coefficient was considered in addition to the slope and length of the river. In the SCS_{lag} method, the factors involved were length, slope, and curve number representing infiltration and surface storage. Watershed area and surface storage were considered along with the length and slope factor, in Simas and Hawkins method, leading to the most accurate TC values obtained. Another method used was the NRCS method, in which runoff flow in a watershed is divided into three parts: sheet flow, concentrated shallow flow, and open channel flow. As indicated in Table 6, the accuracy of this method was about 82%.

The average slope, length of the main river, and the area are distinctive and numerously considered parameters in the empirical relations. Although all these three parameters might be included in one empirical equation, the calculated TC is far different from the actual value, as observed in Bransby-Williams's equation. Such differences might arise from the fact that each empirical method is developed for a certain area. For example, the Kirpich equation has been developed in the Tennessee watershed in the United States. The second reason is that different models are derived from different concepts and even different definitions of TC. Further investigation of the equations reveals that the TC values obtained from such equations depend on the number of parameters and the type of parameters involved. If the empirical equation is only a function of the length and average slopes of the main river, such as the Chow and Espy equations, or when the n coefficient is also included, the result of the empirical method is much smaller than the actual value of concentration time. In conclusion, some parameters, namely equivalent circle diameter, distance from the watershed centroid, and difference in main river elevation, are less important. Therefore, the estimated value of the empirical formula is much larger than the actual TC, which leads to an incorrect estimation of the peak flow. As a result, the cost of river basin management and hydraulic structure construction becomes higher. For a more accurate estimation, the parameters affecting the TC must be clearly identified. Therefore, a sensitivity analysis was carried out to investigate the effect of each variable on TC values. It is noteworthy that sensitivity analysis does not imply the accuracy of the models. However, due to the experimental nature of the used models, of which many parameters (such as Manning's roughness coefficient, curve number, runoff coefficient, etc.) cannot be precisely measured, one has to rely on the estimated values based on his field experiences for such inputs. Therefore, it is admissible that poor performances of some models can be caused by the approximative nature of the input values and not necessarily the accuracy of the models. Obviously, the more sensitive a model is to these parameters, the more its accuracy might be affected by the certitude of such inputs. Therefore, performing a sensitivity analysis in this study was not for the purpose of comparing the models' accuracy, but because of having a simultaneous view of their accuracy and sensitivity to different inputs.

Sensitivity Analysis Results

Tables 7–11 list the sensitivity coefficients of models in categories I to V to different variables. Negative values indicate the inverse relationship between the variable and TC. It can be concluded that increases in Sr, Sb, H, D, E, CN, C, and P24, reduce TC. Due to the increase of flow kinematic head, the increase of slope identification variables (Sr, Sb, and H) leads to the increase in runoff velocity and the decrease of TC. The increase in CN and C parameters results in a decrease in TC, by increasing the percentage of water flowing in the form of surface flow compared with the depression and subsurface flow.

Table 7. Sensitivity coefficients of the methods based on *L*, L_t, S_r and A (category I).

Equation	S_L	S_{Sr}	S_{Lt}	S_A
Kirpich-Pennsylvania	0.772	−0.522	-	-
Kirpich-Tennessee	0.772	−0.400	-	-
Chow	0.644	−0.332	-	-
Espey	0.364	−0.185	-	-
US Corps of Engineers	0.763	−0.196	-	-
Temez	0.763	−0.196	-	-
Carter	0.604	−0.311	-	-
Johnston and Cross	0.504	−0.522	-	-
Picking	0.670	−0.345	-	-
Haktanir and Sezen	0.843	-	-	-
Sheridan	0.921	-	-	-
Van Sickle	0.132	−0.067	0.132	-
Bransby –William	1.000	−0.206	-	−0.103
Pasini	0.337	−0.522	-	0.337
California Curvets Practice (CHPW)	1.153	-	-	-
Flavel	-	-	-	0.544
Pilgrim and Mac Dermott	-	-	-	0.384

Table 8. Sensitivity coefficients of the methods based on S_b, *C*, *CN* and *D* (category II).

Equation	S_L	S_{Sr}	S_{S_b}	S_D	S_A	S_{CN}	S_c	S_{lag}
William	1.000	-	−0.206	−1.072	0.404	-	-	-
Bransby Williams	1.000	-	−0.206	−1.072	0.404	-	-	-
SCSlag	0.802	−0.522	-	-	-	−2.357	-	-
Simas and Hawkins	−0.623	−0.154	-	-	0.598	−1.613	-	-
Kerby	0.474	-	−0.243	-	-	-	-	0.474
TXDOT	0.504	-	−0.345	-	-	-	−0.528	-

Table 9. Sensitivity coefficients of the methods based on P_{24} (category III).

Equation	S_L	S_{Sr}	S_n	S_A	S_{lca}	S_{P24}
Arizona DOT	0.254	−0.206	-	-	0.254	0.102
US Army Corps of Engineers	0.540	−0.076	-	-	-	−0.448
Morgali and Linsley	0.604	−0.311	0.604	-	-	−0.416
Kadoya and Fukushim	-	-	-	0.224	-	−0.363

Table 10. Sensitivity coefficients of the methods based on Elevation (category IV).

Equation	S_L	S_H	S_A	S_E
Bransby–William	1.198	−0.206	−0.103	-
Ventura	0.504	−0.522	0.504	-
Pickerin	1.153	−0.400	-	-
Basso	1.153	-	-	−0.400

Table 11. Sensitivity coefficients of the methods based on n (category V).

Equation	S_L	S_{Sr}	S_{Sb}	S_n	S_i
Yen and Chow's	0.604	−0.522	-	0.604	-
Hathaway	1.000	-	−0.522	1.000	-
NRCS	-	−0.361	−0.078	0.150	−0.098

In watersheds with larger Ds, smaller elongation ratios lead to smaller travel time and higher peaks of the flow hydrograph, resulting in a decrease in TC. Furthermore, an increase in P24 indicates higher average rainfall intensity within 24 h, which in turn prompts an increase in runoff flow velocity and a decrease in TC. Meanwhile, increasing the parameters related to the length of the flow path (L and Lt) leads to a TC increase due to the longer travel time. In addition, larger "n" values represent higher energy losses due to bed friction and lower flow rates, leading to larger values of TC.

The models were the most sensitive to L, CN, Sr, A, and n variables, respectively (with average values of S as 0.69, 0.28, 0.19, 0.083, and 0.081, respectively), among which the main river length variable is of great importance due to its participation in almost all models (94% of the total). The models were the least sensitive to Lt, Lca, E, tlag, and P24 variables, respectively, with average S values of 0.003, 0.005, 0.008, 0.01, and 0.02, respectively. Among Class I relations, California Culverts Practice was found to be the most sensitive model to the main river length parameter, with S values of 1.15 (Table 7). Following that model, Bransby-Williams, Sheridan, and Haktanir–Sezen models showed the highest sensitivity to L, with S values of 0.1, 0.92, and 0.84, respectively. The lowest sensitivity to L was observed in the Van Sickle model (with S 0.13). This model also showed the lowest sensitivity to river slope (S = −0.67). According to Table 7, the highest sensitivity to Sr is seen in the Johnston and Cross and Kirpich-Pennsylvania models. Among the area-based models, Flavell, Pilgrim, and McDermott were respectively the three most sensitive ones to the watershed area, while the Bransby-Williams model showed the lowest sensitivity to A. It should be noted that high sensitivity to "A" in both Flavell, Pilgrim, and McDermott models is predictable due to the dependence of these two models on the watershed area solely. According to Table 8, of the 12 models in category II, the highest sensitivity to basin slope is related to the SCS_{lag} model (with S values of −0.52), while the Williams and Bransby-Williams models were least sensitive to Sb (S = −0.21). It seems that the Simas and Hawking and SCSlag have the maximum and minimum sensitivity to CN, respectively.

The U.S. Army engineers Morgali and Linsley, Kadoya and Fukushima, and Arizona DOT models were less sensitive to P24 rainfall (Table 9). The Ventura model showed the highest sensitivity to elevation differences. The lowest sensitivity to "H" is met in the Bransby-Williams model and the highest was Ventura (Table 10). According to Table 11, the highest sensitivity to the roughness coefficient was related to the Hathaway model (with a value of S, 1), while the lowest sensitivity to n was observed in Yen and Chow's (with S = 0.64).

In short, the different common TC methods may reveal significantly different estimations for a specific watershed with constant physical characteristics. It is therefore suggested to use methods such as Simas and Hawkins and SCSlag which include important and effective parameters on the time of concentration. Among the models of category 1, the Haktanir and Sezen model has the highest accuracy of TC estimation (Table 2), but due to its sole dependence on L, it cannot be compared with other models in terms of sensitivity. On the other hand, due to being univariate, the sensitivity of this model to L is obviously higher than other models. The results of Table 7 show that Temez and Bransby –William models, which are among the three models with high accuracy in category 1, had relatively lower sensitivities to the applied parameters. However, low sensitivities do not necessarily entail the high accuracy of the model, Van Sickle and Passini models, for instance, are the least sensitive models to input parameters which resulted in relatively high Res in Table 2.

Between the models of Category 2, the lowest sensitivity to input parameters is observed in the Simas and Hawkins model (Table 8). This is probably one of the reasons why this model has the highest accuracy compared to all experimental models. Sensitivity coefficient values obtained in the most accurate model of Category 3, i.e., Kadoya and Fukushima are relatively small. However, the results of the Arizona DOT model with minimum sensitivity coefficient values were not reliable (Table 9). According to Table 10, Bransby–William, as the most accurate model in Category 4, has the smallest values of sensitivity coefficient to input parameters. Similar results were obtained among Category 5 models, in which NRCS and Yen and Chow, respectively with the lowest sensitivities to the inputs, were the two models with the lowest Res (Tables 7 and 11).

3.2. Hydraulic Simulation

"Water parcel", used in TC definition, is supposed to be the bank-full discharge, which is compatible with those reported by [30,42,43]. For the estimation of bank-full discharge, river cross-sections with 50 meters intervals were obtained from the digital elevation model.

Manning's roughness coefficient was calibrated for the numerical simulation. To do this, some cross sections were mapped along with water depth. The flow velocity was estimated by the floating object method. To determine Manning's value in the simulation, it should be mentioned that Manning's was not considered for the whole watershed area, it is determined just for the river path. So, in field observation through the river, the length is divided into some shorter parts, and after the velocity and cross-section area were determined, Manning's equation was solved reversely to obtain Manning's roughness coefficient of each part. Since the value was nearly same in the all parts, the mean weight of Manning was considered for the river path. So, the same value of Manning's roughness (0.045) was applied in the simulation for the whole river length.

This value was in agreement with that reported by Chow, [44] in tables recommending Manning's roughness coefficient values for different waterways. As described in this table, the average Manning's roughness coefficient value for natural minor clean and meandering streams with some pools and shoals is proposed to be 0.045.

Cowan's method was also examined to ensure the results. In this method Manning's roughness coefficient is predicted by the following relation:

$$\mathrm{n} = (\mathrm{n}_0 + \mathrm{n}_1 + \mathrm{n}_2 + \mathrm{n}_3 + \mathrm{n}_4)\,\mathrm{m}_5 \quad (6)$$

Referring to Cowans's table [38] and selecting coarse gravel for bed materials (n_0 = 0.028), minor degree of irregularity (n_1 = 0.005), variations of channel cross section as alternating occasionally (n_2 = 0.005), relative effect of obstacles as negligible (n_3 = 0.0), low vegetation (n_4 = 0.005–0.01) and minor degree of meandering (m_5 = 1.0), the Cowan's relation yields n = 0.045, which is compatible with previous results.

After Manning's roughness coefficient value was determined, the cross sections were then introduced to the one-dimensional HEC-RAS model. Normal depth with a 0.03 slope was set as a downstream boundary condition. The bank-full discharge was then estimated through trial and error by choosing various flow discharges as upstream boundary conditions and examining outputs at different sections. Due to the non-uniform cross sections and slopes along the river, the bank-full discharge was estimated as a range between 2.53 and 3.53 m^3/s.

The TC was then estimated by a two-dimensional hydraulic simulation of the water parcel flowing along the longest watercourse. For this purpose, the bank-full discharges were introduced to the two-dimensional model as upstream boundary conditions. The uniform flow with a slope of 3% was defined as a downstream boundary condition. The computational cell sizes were determined by trial and error in order to stabilize the numerical model. Computational cells of 1 to 20 m sizes with time steps of 1 s to 1 min were tested in the trial-and-error process. Finally, a computational cell size of 4 m and a time step of 10 s were chosen. After the mesh size was computed, the boundary conditions were introduced to the two-dimensional model. Since the bank-full discharge was defined within an interval between 2.53 and 3.53 m^3/s, the simulation was performed twice, each time with one side of the range (displayed as Q_b (max) and Q_b (min), respectively). Figure 2 illustrates the process of estimating TC by two-dimensional hydraulic simulation.

The simulation results for the two-dimensional model are shown in Table 12. According to this table, the best results (compared with other empirical relations) are obtained when the upper bound of the bank-full discharge (Q_{bmax}) is introduced as the upstream boundary condition of the numerical model. Even compared with the empirical method, the lower limit produces acceptable results. For numerical simulation, the maximum error of TC prediction is limited to 27%, while for empirical relationships, the corresponding error exceeds 300%. This shows the accuracy of the numerical simulation in the prediction of TC value as an important parameter in hydrological studies without considering the climatic or regional conditions of the watershed. This can be related to the significant effect of spatial changes in topography included in the numerical model, which are neglected in the empirical relations. Due to the limited number of parameters, empirical methods are usually developed as experimental mathematical power equations between TC and the average river slope, watershed area, and some other parameters collected in a limited number of watersheds. On the contrary, the two-dimensional simulation method can directly simulate the water parcel transfer through continuity and momentum equations, utilizing actual details of the geometry of a watershed provided in DEMs. Therefore, involving a great number of parameters, the two-dimensional method can be obtained in any desired watershed, while the empirical models are developed for a limited and specific number of watersheds and climates. In addition, with satellite information currently available, one may access free topographic data required in order to construct the geometry of watersheds in detail. However, the numerical computation of the proposed method should be accepted to gain reliable results.

Based on the results of sensitivity analysis, the seven most distinctive parameters identified are main river length, Curve Number, main river average slope, watershed area, Manning's roughness coefficient, and watershed average slope. Most of the above-mentioned parameters (except CN) are considered in the two-dimensional hydraulic simulation method in the HEC-RAS model. Compared with the measurement fields shown in Table 12, the higher accuracy of parameter evaluation in the model and their significant influence on the TC value result in a higher accuracy of the TC value.

Limitation of the current study:

To represent underlying terrain, maps with different resolutions can be applied. Therefore, a map with a less special resolution, for instance, more than 30 m, cannot represent rivers with a width of 15 m. Therefore, this limitation should be taken into account. In addition, to run a fast 2D simulation, users need at least a 3.4 GHz or higher CPU processor, otherwise, the simulation would be time-consuming.

Table 12. TC (h) and RE (%) for Two-Dimensional Simulation.

Simulation Discharge (m^3/s)	Estimated TC (h)	RE (%)
Q_b(max)	1.8	3.1
Q_b(min)	2.22	26.98

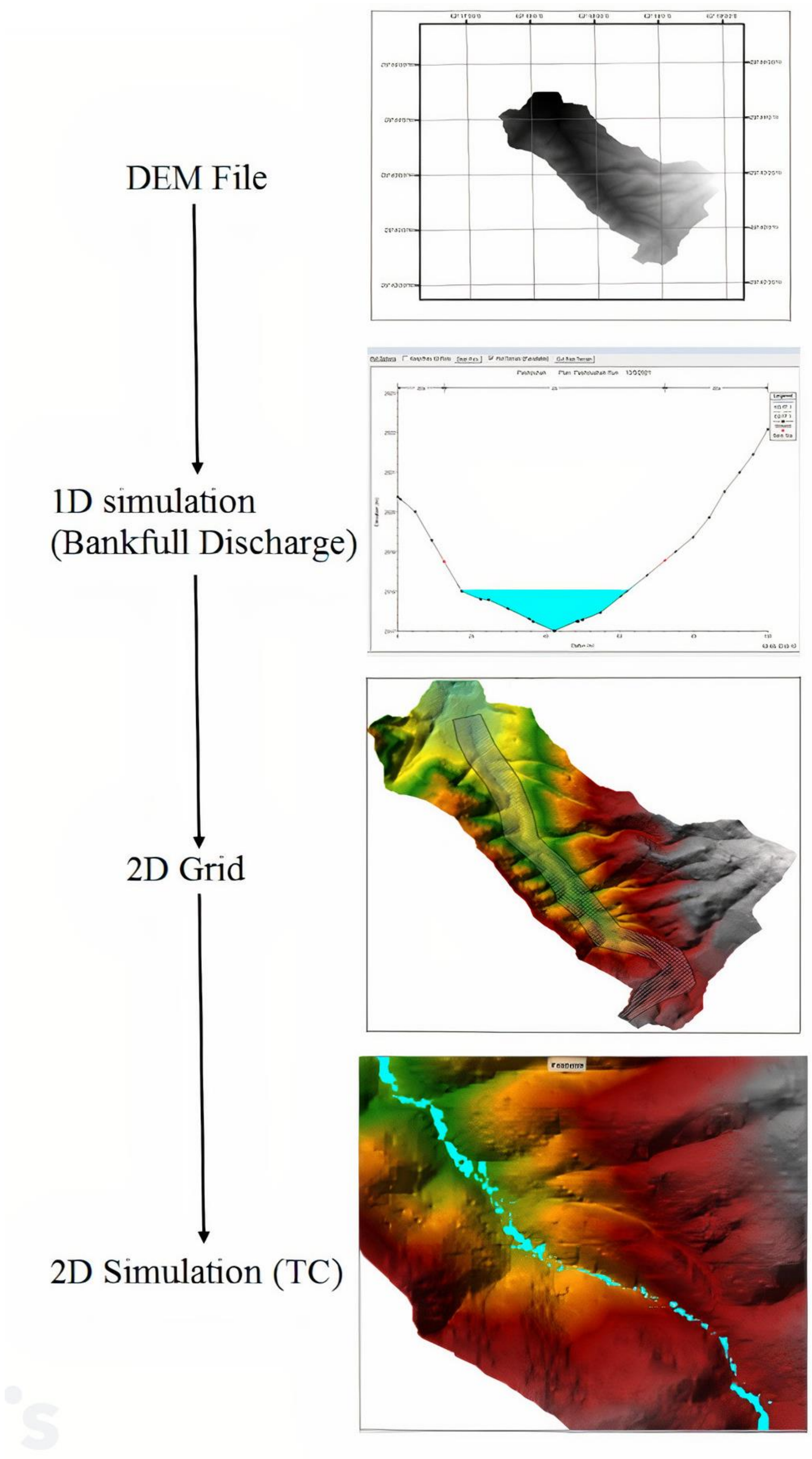

Figure 2. Flowchart describing the proposed procedure for calculating TC.

4. Conclusions

In this study, hydraulic simulation was introduced and tested as a method for estimating TC. In the case of the Aliabad watershed in Fars province, different empirical methods were also evaluated and compared with the TC values obtained from salt solution tracing. Empirical relations have shown different precisions, probably as a result of being developed for different reference watersheds. Such a variety of results and accuracies may have also arisen from different concepts and even different definitions of TC and/or the limited number of parameters being involved in these relations. A closer comparison reveals that TC values obtained by each relation depend on the region and number of parameters involved. Sensitivity analysis of the empirical methods was conducted based on the non-dimensional relative sensitivity coefficient. The models were the most sensitive to main river length, Curve Number, main river average slope, watershed area, Manning's roughness coefficient, and watershed average slope, among which the main river length variable was of great importance due to its participation in almost all models.

The results indicate that among empirical relations, the TC value obtained from the F and Hawkins equation is much closer to the measured value and is considered the best empirical equation for the Aliabad watershed. This equation involves river length and slope, watershed area, and surface storage. After Simas and Hawkins, the equations developed by, SCS_{lag}, Yen and Chow, and NRCS gave the closest estimations to the actual concentration time, respectively. The results of this study can be used to calculate the TC of watersheds with similar characteristics.

The results of the HEC-RAS two-dimensional model show that the accuracy of simulation of TC using bank-full flow discharge varies from about 3.93%t to about 26.976%, which is acceptable compared with the empirical methods, in which the error was up to 300%. HEC-RAS two-dimensional model provided acceptable results in simulating TC. In this model, the water parcel travel is simulated, using terms of topography, land features, and roughness coefficient. It is true that the computational cost of the hydraulic simulation is higher than that of empirical relations, but because TC is an important factor, which may be in turn used for the preparation of complicated hydraulic models for flood risk mappings and similar studies, the calculation cost is welcome to meet the conditions.

Generally, the results show that the two-dimensional HEC-RAS model, Simas and Hawkins relation gave TC values much closer to those obtained from the salt solution tracing, respectively. Therefore, the two-dimensional simulation is considered the best TC estimation method. After these methods, the equations with the closest results to the measured value were: SCS_{lag}, Yen and Chow, and NRCS, respectively. The results of mentioned empirical relations can be used to calculate TC in watersheds with similar characteristics. Additionally, due to the existence of measurement data, the results of this study can be used as a criterion for measuring TC in similar hydrological studies. Unlike empirical methods, hydraulic simulation is a method that can be used in any area, especially in areas with no hydrometric and rainfall information, where graphical methods are of no use.

Future works:

1. It is recommended to consider the graphical method (rainfall-runoff) as an alternative to salt solution tracing in a gauged basin as a benchmark to compare 2D simulation output.
2. In this study, to introduce bathymetry into the model, the DEM file with a resolution of 12.5 m from the Advanced Land Observation Satellite (ALOS) was employed. It is recommended to apply higher resolution satellites or other methods such as using a drone to survey maps of the area or bathymetry with high resolution in order to investigate the map resolution effect on TC.

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