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The Influence of Concentration Time Parameters in Model Development Surface Runoff

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Abstract: Surface runoff response is strongly controlled by the time of concentration (Tc), which governs hydrograph timing, peak discharge, and critical storm duration in watershed and urban drainage analyses. However, Tc remains one of the most inconsistently defined and estimated parameters in hydrological modelling, particularly under rapid urbanization and changing rainfall conditions. This study presents a systematic literature review to examine how Tc parameters influence surface runoff model development and predictive reliability. Using the PICOS framework, Scopus-indexed studies were screened and synthesized to compare the definition, estimation, and application of Tc across empirical, hydraulic, hydrological, GIS-based, and data-driven modelling approaches. The review shows that differences in Tc formulation produce substantial variation in runoff predictions, especially in peak discharge estimation, hydrograph response, and flood-prone area assessment. Studies consistently indicate that fixed Tc assumptions may oversimplify urban catchment behaviour, whereas dynamic or context-sensitive Tc representations tend to improve model realism under conditions of changing imperviousness, drainage connectivity, and rainfall variability. The findings highlight Tc as a controlling parameter rather than a simple input constant, and emphasize the need for careful equation selection, calibration, and contextual interpretation in future surface runoff studies.

Keywords: concentration time, surface runoff modelling, hydrological model, flood risk management, urban drainage

1. Introduction

Surface runoff is a fundamental component of the hydrological cycle because it governs the transformation of rainfall into overland flow, channel response, and, ultimately, flood generation. In urban and peri-urban catchments, this process becomes more complex as land-use change and urban expansion increase impervious surfaces, reduce infiltration capacity, and accelerate runoff conveyance. As a result, urbanized watersheds generally exhibit higher runoff volumes, shorter hydrological response times, and greater susceptibility to flooding than natural catchments. These conditions explain why urban runoff continues to be a major concern in hydrological research and engineering practice, particularly in relation to stormwater management, drainage design, and flood mitigation [1],[2], [3].

Within this context, the time of concentration (Tc) is one of the most important hydrological parameters because it represents the time required for runoff to travel from the hydraulically most distant point of a catchment to its outlet [4], [5], [6]. In practical terms, Tc controls hydrograph timing, peak discharge estimation, and critical storm duration, and is therefore embedded in many empirical, conceptual, and physically based rainfall–runoff models [7], [8]. In engineering applications, Tc is widely used in urban drainage design, watershed response analysis, runoff routing, and flood forecasting [9], [10], [11]. Because Tc influences the synchronization of runoff contributions across a catchment, even relatively small differences in its estimation can lead to substantial variations in predicted peak discharge and flood timing [5], [12], [13].

The importance of Tc becomes even more evident in urban environments, where hydrological responses are strongly modified by anthropogenic change. The shortening of effective flow paths due to impervious cover, drainage infrastructure, and altered surface connectivity can significantly reduce Tc and increase peak discharge. Previous studies have shown that increasing the extent of sealed or watertight surfaces accelerates runoff travel toward urban drainage channels, thereby aggravating flood hazards and imposing additional stress on existing drainage systems [14], [15]. In this sense, Tc is not only a descriptive watershed parameter, but also a controlling variable that links land-use dynamics, runoff generation, and flood response.

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Although Tc is widely applied, its conceptualization and estimation remain far from uniform. Hydrological literature has interpreted Tc from graphical, empirical, hydraulic, morphometric, semi-empirical, numerical, and process-based perspectives, each relying on different assumptions regarding flow path, velocity, slope, roughness, and contributing area [4], [5], [6], [13], [15]. This inconsistency has long been recognized as both a conceptual and practical problem in hydrology. Beven [9], for example, noted that the traditional interpretation of Tc as the travel time of a single water particle may be insufficient, since watershed response is more appropriately governed by flow celerity and integrated system behaviour than by particle velocity alone. Consequently, different estimation methods may produce markedly different Tc values even for the same watershed, which in turn can alter hydrograph timing and peak discharge magnitude [3], [12], [16].

This issue becomes more critical in urbanized catchments, where artificial drainage systems, impervious surfaces, modified slopes, and engineered flow paths often violate the assumptions underlying conventional Tc equations. Several studies have shown that equations originally developed for rural or natural basins do not always perform reliably when directly applied to urban environments [3], [7], [17], [18], [19]. Depending on watershed characteristics, drainage configuration, and parameter sensitivity, such equations may overestimate or underestimate Tc relative to observed or benchmark conditions [3], [7]. These findings indicate that Tc estimation should not be treated merely as a routine computational step, but rather as a critical modelling decision that directly affects runoff realism and the reliability of design outcomes.

In addition to land-use and drainage modifications, antecedent soil moisture and other initial hydrological conditions also influence Tc and overall runoff response. Variations in soil moisture can alter infiltration rates and modify the travel time required for water to reach the outlet [13]. In urban systems, this variability is compounded by stormwater infrastructure, which can dynamically redirect or accelerate runoff pathways. As a result, Tc should be understood as a context-dependent parameter rather than a fixed watershed constant. This has important practical implications because uncertainty in Tc may bias peak discharge predictions and consequently affect the planning and performance of flood control and rainwater management systems [20], [21], [22].

Recent advances in hydrological modelling have enabled more detailed representation of spatial heterogeneity, drainage network interactions, and event-based runoff processes. However, the predictive performance of such models still depends heavily on the quality and representativeness of key parameters, including Tc [9], [10], [21]. Uncertainty studies have further shown that parameter selection and structural assumptions can strongly influence urban runoff simulation results, especially under conditions of increasing imperviousness, land-use change, and stormwater intervention scenarios [18]. Therefore, Tc should not be viewed simply as an input value, but as a controlling parameter whose interpretation affects model reliability, transferability, anddecision relevance.

Despite the broad literature on Tc equations and rainfall–runoff modelling, an important knowledge gap remains. Existing studies have mainly focused on proposing new Tc equations, comparing selected estimation formulas, or applying runoff models to case-study watersheds [4], [5], [13], [15]. Much less attention has been given to systematically synthesizing how different Tc parameterizations influence the development and performance of surface runoff models across varying hydrological contexts, particularly under urbanization, land-use change, and climate-related stressors [22], [23]. Likewise, although nature-based solutions, stormwater ponds, and resilience-oriented drainage strategies are increasingly discussed in flood mitigation research, their hydrological evaluation still depends fundamentally on how watershed response time is conceptualized in the underlying models, [24], [25], [26]. This indicates the need for a structured review that places Tc at the centre of surface runoff model development rather than treating it as a secondary technical variable.

Accordingly, this study presents a systematic literature review on the influence of time of concentration parameters on surface runoff model development. The review examines how Tc is defined, estimated, and incorporated into runoff modelling frameworks; how differences in Tc treatment affect peak discharge estimation, hydrograph response, and flood- prone area assessment; and how these implications vary across empirical, hydraulic, GIS-based, and data-driven approaches [9], [11]. By synthesizing findings from studies on urbanization, land-use change, hydrological uncertainty, and evolving modelling techniques, this paper seeks to clarify the methodological role of Tc and to provide a stronger scientific basis for selecting appropriate Tc representations in future surface runoff studies [19], [22]. Ultimately, this review is expected to contribute to hydrological science and engineering practice by offering a more integrated understanding of Tc as a key determinant of runoff model behavior, with practical relevance for urban drainage design and flood risk management.

2. Methodology

This study employed a Systematic Literature Review (SLR) to synthesize current knowledge on the role of time of concentration (Tc) parameters in surface runoff modelling. The review procedure was structured in accordance with the PRISMA framework to ensure a transparent, reproducible, and logically traceable process of identification, screening, eligibility assessment, and final inclusion of relevant studies.

The literature search was conducted primarily through the Scopus database using combinations of keywords related to time of concentration, surface runoff, hydrological modelling, runoff prediction, and flood-prone area assessment. The search strategy was designed to capture studies discussing Tc either as a direct model input or as a controlling parameter affecting runoff response, hydrograph characteristics, peak discharge estimation, and flood interpretation. To improve thematic relevance, the search terms were formulated to cover both conceptual discussions of Tc and its practical application in empirical, hydraulic, GIS-based, and data-driven hydrological models.

The inclusion process focused on peer-reviewed journal articles that explicitly examined the use of Tc in runoff modelling or hydrological response analysis. Articles were retained when they discussed Tc estimation methods, compared fixed and variable Tc approaches, or evaluated the implications of Tc selection for model outputs such as peak discharge, peak time, runoff volume, model accuracy, or flood susceptibility. Studies that did not address Tc substantively lacked sufficient methodological information, or were not directly relevant to surface runoff modelling were excluded. After the initial search, titles and abstracts were screened first,

followed by full-text evaluation for articles meeting the relevance criteria.

Data extraction was then carried out systematically to identify the main characteristics of each selected study, including study context, watershed type, modelling approach, Tc formulation, input parameters, and reported hydrological outcomes. The extracted information was synthesized qualitatively to examine recurring themes, methodological differences, and the implications of Tc parameterization for runoff model development. Particular attention was given to the contrast between fixed and dynamic Tc representations, the sensitivity of model outputs to Tc assumptions, and the broader relevance of these findings for urban hydrology, flood simulation, and watershed management.

2.1 Theory and Calculation

Time of concentration (Tc) is a fundamental parameter in hydrological modelling because it represents the time required for runoff from the hydraulically most distant point of a catchment to reach the outlet. Tc plays a central role in controlling peak discharge, hydrograph shape, and the critical rainfall duration that produces maximum runoff. In practical hydrological applications, including the Rational Method and event-based runoff models, Tc is therefore treated as a key response-time parameter rather than merely a geometric descriptor of the watershed [2].

Conceptually, Tc may be represented in two ways. The first is constant Tc, in which the parameter is assumed to remain fixed and is derived from watershed characteristics such as flow length, slope, and surface roughness. The second is variable or dynamic Tc, in which the effective concentration time changes according to rainfall intensity, antecedent wetness, runoff depth, drainage connectivity, and land-use conditions, especially in urbanized basins [27]. Differences in Tc estimation directly affect the reliability of surface runoff prediction. An underestimated Tc tends to produce an unrealistically high peak discharge, whereas an overestimated Tc may delay the simulated hydrograph peak and reduce predictive realism [16], [17], [27], [28].

2.2 Flow Path Components

In general, the total time of concentration can be expressed as the sum of travel times along the major runoff path components, including sheet flow, shallow concentrated flow, and channel flow [17], [27].

$$T_c = t_{sheet} + t_{shallow} + t_{channel} \quad (1)$$

where:
T_c = Total concentration time (hours or minutes)
t_{sheet} = sheet flow time
$t_{shallow}$ = shallow flow time
$t_{channel}$ = channel flow time

2.3 Empirical Formulas and Commonly Used Physical Approaches

Several empirical and semi-physical equations are commonly used to estimate Tc, depending on watershed scale, data availability, and the dominant runoff pathway. Comparative studies show that no single equation is universally superior, and model sensitivity to Tc often depends on local watershed characteristics, especially in urbanized basins [17], [27], [28].

(a) Kirpich (1940)

Used for small watersheds with well-defined channels:

$$T_c = 0.0078\, L^{0.77}\, S^{-0.385} \quad (2)$$

where:
T_c = time of concentration (minutes),
L = length of main flow path (m),
S = slope (m/m).

(b) Bransby Williams (ASDOT 1995)

The Bransby Williams method is also widely applied for larger or more rural catchments and is commonly used in comparative Tc studies [17], [28]:

$$T_c = 0.605\, L(100Sc)^{-0,2}\, A^{-0.1} \quad (3)$$

where:
T_c = time of concentration (hours),
A = catchment area (km²),
L = main flow length (km)

(c) Natural Resources Conservation Service (NRCS) Sheet Flow Equation

For short overland flow segments, Tc can be estimated using the NRCS sheet flow equation, which incorporates roughness, rainfall, flow length, and slope [27], [28], [29]:

$$t_{sheet} = \frac{0.007\,(n\,L)^{0.8}}{P_2^{0.5}\, S^{0.4}} \quad (4)$$

where:
t_{sheet} = sheet flow travel time (hours),
n = Manning's coefficient of roughness
L = length of thin flow trajectory (m)
P_2 = 2-year return period 24-hour rainfall depth (mm)
S = surface slope (m/m)

(d) Channel Flow (Manning's Equation)

For runoff traveling through defined natural or artificial channels, travel time may be estimated using flow velocity derived from Manning's equation [28], [29]:

$$t_{channel} = \frac{L}{V} \quad (5)$$

$$V = \frac{1}{n}\, R^{\frac{2}{3}}\, S^{\frac{1}{2}} \quad (6)$$

where:
$t_{channel}$ = flow travel time in a channel (hours or seconds)
L = channel length (m)
V = Flow velocity (m/s)
R = Hydraulic radius (m)
S = channel slope (m/m)
n = Manning's coefficient of roughness

2.4 Variable Concentration Time (Dynamic TC)

Recent studies have shown that Tc should not always be assumed constant, particularly in urban basins and under event-specific hydrological conditions. Dynamic Tc reflects the idea that watershed response time may vary with rainfall intensity, antecedent moisture, runoff depth, and drainage-network efficiency [16], [30]. Two common interpretations are:

a. Event-Specific Tc is recalculated for different hydrological conditions (dry, wet, low–high rainfall intensity) to analyze sensitivity and its impact on the timing and magnitude of peak flows.
b. State-Dependent Tc was updated iteratively during the simulation by considering changes in flow speed due to inundation depth and rainfall intensity. This approach is

commonly applied in dynamic models such as HEC-HMS (kinematic waves) and SWMM (dynamic flow routes).

2.5 Sensitivity and Uncertainty Analysis

i. Nash–Sutcliffe Efficiency (NSE)
ii. Root Mean Square Error (RMSE)
iii. Percent Bias (PBIAS)

2.6 Peak discharge error (%) and peak time (minutes)

Sensitivity tests can be performed by varying input parameters, such as slope, roughness, and track length, by ±10–30% to observe their impact on the resulting Tc change and peak discharge.

2.7 Practical Steps for Calculation

i. Delineation of sub catchment areas involves determining the longest flow trajectory and dividing it into sheet flow, shallow flow, and channel flow segments.

Tc is a very sensitive parameter in hydrological models, and uncertainty evaluation is important to ensure the reliability of the model results. Some standard metrics used to assess model performance are:

ii. Parameter determination is in the form of measuring the trajectory length (L), slope (S), and roughness (n) for each segment.
iii. Travel Time is calculated for each segment using the Manning or NRCS equation, then summing it up to get the total Tc.t_i.
iv. Cross-validation is in the form of comparing the results of the calculation with empirical formulas (Kirpich, Giandotti) to ensure consistency.
v. Integration into Hydrological Models in the form of using Tc in determining hydrograph unit parameters or critical rainfall duration in models such as HEC-HMS and SWMM
vi. Model Performance Evaluation is in the form of an analysis of the influence of Tc on model accuracy and flood prediction reliability

3. Results And Discussion

3.1 Multidimensional Analysis

The multidimensional radar analysis compares six principal approaches for estimating the time of concentration (Tc) using five evaluation criteria: predictive accuracy, computational efficiency, data availability, ease of application, and physical interpretability. The comparison shows that physically based approaches, particularly two-dimensional hydraulic simulation and particle-tracking methods, provide the strongest physical representation of runoff travel processes because they explicitly capture spatial heterogeneity, flow routing, and hydraulic interactions within the catchment. Their main limitation, however, lies in their high computational demand and extensive data requirements, which may restrict their use in routine design applications or rapid decision-making.

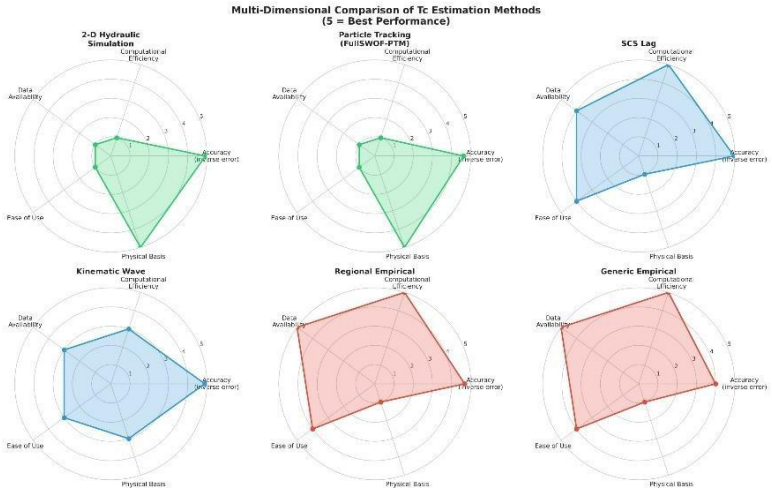

Fig. 1 - Multidimensional Comparison of Tc Estimation Methods

By contrast, empirical formulas such as Kirpich, Giandotti, and regional equations remain attractive because they require relatively simple inputs and are easy to apply in preliminary studies. Nevertheless, their weaker physical basis makes them less responsive to land-use change, drainage modification, and event-scale hydrological variability. Semi-empirical approaches, including SCS Lag and Kinematic Wave, occupy an intermediate position by offering a more balanced trade-off between practicality and hydrological realism.

Overall, Fig. 1 indicates that the selection of a Tc estimation method should be guided by study purpose, data availability, and watershed complexity. Empirical methods are still useful for rapid design estimates, whereas semi-empirical and physically based approaches are more suitable for urban runoff analysis, scenario simulation, and flood-risk assessment, where temporal variability in Tc must be represented more explicitly

3.2 Bibliometric Analysis

The bibliometric mapping presented in Fig. 2 reveals four closely connected research clusters: (i) hydrological modelling, calibration, and validation; (ii) Tc estimation and model performance assessment; (iii) urbanization, land-use change, and storm response; and (iv) spatial parameters and supporting hydro-meteorological data. The density of links among keywords such as HEC-HMS, validation, rainfall intensity, urban area, and sub-watershed indicates that Tc is increasingly positioned as a bridging variable between

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watershed characteristics and runoff response. This pattern also suggests that contemporary Tc research is no longer limited to equation comparison, but is progressively integrated with distributed modelling, calibration procedures, and urban hydrological analysis.

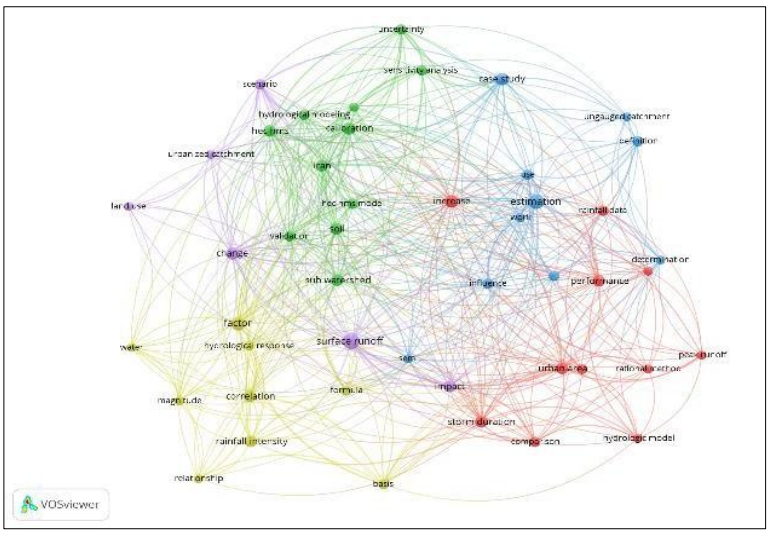

Fig. 2 - Bibliometric Analysis

Shows four main clusters of research related to Tc, namely:

1. Hydrological modelling and calibration/validation (keywords: HEC-HMS, hydrological modelling, sensitivity analysis),
2. Estimation and evaluation of model performance (keywords: estimation, performance, peak runoff),
3. Urbanization and land use change (keywords: urban area, storm duration, land use), and
4. Spatial parameters and supporting data (keywords: rainfall intensity, soil, sub-watershed).

The density of the relationship between keywords in the HEC-HMS and validation areas showed the dominance of research using a distributed model with an explicit calibration process for the Tc parameters. Emphasizing the important role of Tc as a connecting parameter between land use dynamics and runoff response to extreme rainfall events.

3.3 Performance Analysis of Concentration Time Estimation Method (Tc)

Figure 3 summarizes the reported performance of several Tc estimation methods using the Nash-Sutcliffe Efficiency (NSE) metric and its 95% confidence interval. The overall pattern shows that the Kinematic Wave approach achieves the strongest and most stable performance, with mean NSE values exceeding 0.80 and relatively narrow uncertainty bounds. This indicates that methods capable of representing runoff routing processes more explicitly tend to produce more reliable predictions across varying watershed and rainfall conditions.

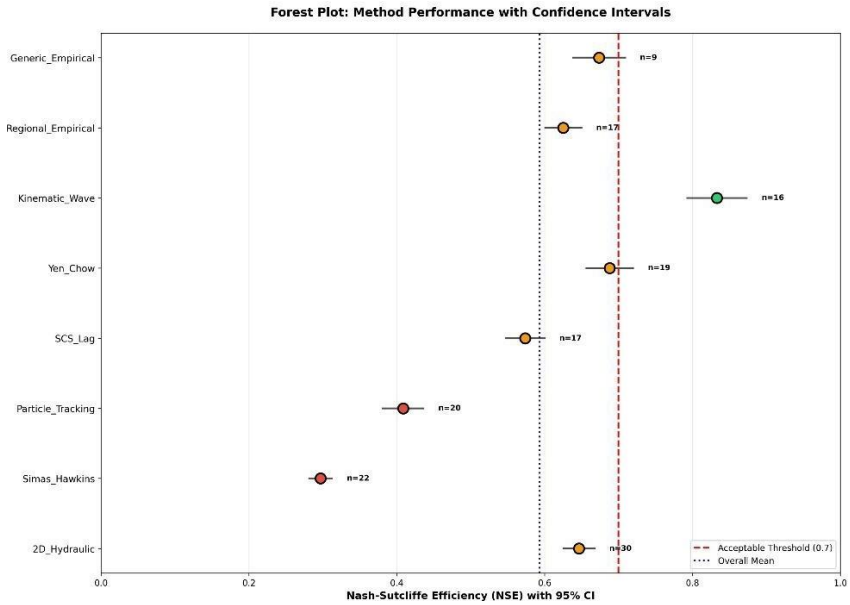

Fig. 3 - Method Performance with Confidence Intervals

Empirical and regional equations generally cluster near the lower end of acceptable performance, often around the NSE threshold of 0.70, and display wider confidence intervals. This suggests greater sensitivity to local calibration

conditions and more limited transferability when catchments undergo rapid urbanization or drainage modification. In practical terms, these methods remain useful for screening and preliminary design, but their direct adoption in complex urban settings should be undertaken cautiously.

The SCS Lag and Yen-Chow approaches show intermediate performance, indicating that they may offer a workable compromise between simplicity and physical representativeness. Meanwhile, particle-tracking and two-dimensional hydraulic simulation methods perform well in selected case studies, but their wider uncertainty ranges reflect strong dependence on spatial resolution, hydraulic parameterization, and computational setup. These findings confirm that higher model complexity does not automatically guarantee consistent performance unless supported by adequate data and calibration.

The comparatively low performance of the Simas-Hawkins method further reinforces the importance of methodological fit between Tc formulation and watershed behavior. Taken together, the results in Fig. 3 support the earlier radar analysis by showing that approaches with stronger process representation tend to provide more robust runoff predictions, especially when the catchment exhibits dynamic hydrological responses.

3.4 Systematic Literature Review

The publication trend in Fig. 4 shows limited and scattered output before 2017, followed by a clear increase between 2018 and 2021, when research on urban hydrology, distributed modelling, and high-resolution rainfall data expanded more rapidly. After 2021, publication frequency declines moderately, but this should not be interpreted as reduced relevance. Rather, it reflects a shift toward broader digital-hydrology themes such as artificial intelligence, radar-based forecasting, and real-time prediction systems, in which Tc may be embedded implicitly within model structure rather than treated as an isolated variable.

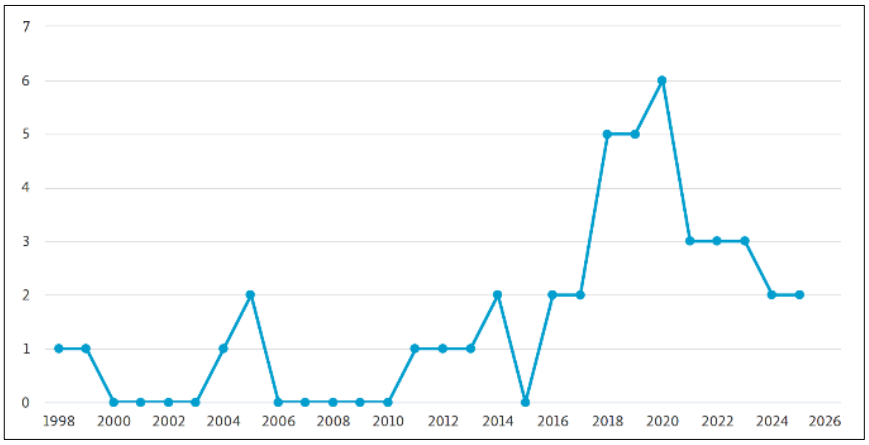

Fig. 4- Publication Trends

The nine studies included in the synthesis cover diverse hydrological settings, including small to medium watersheds, urban and peri-urban basins, restored river systems, and catchments affected by increasing imperviousness. They also represent a broad methodological range, from empirical Tc estimation and semi-distributed hydrological modelling to laboratory experiments and data-driven forecasting using artificial neural networks and weather radar. Across these studies, the principal outcomes assessed were hydrograph accuracy, peak discharge, peak time, runoff response, and, in one case, water-quality implications associated with runoff processes.

The first recurring theme concerns the definition and estimation of Tc. The reviewed studies consistently show that Tc is not a single universally stable quantity; rather, it depends on the conceptual framework, equation structure, and hydrological assumptions applied. Differences in Tc estimation lead directly to differences in critical storm duration, peak discharge, and hydrograph timing, which means that method selection is not merely technical but materially influences model output and interpretation.

The second theme is the contrast between fixed and variable Tc representations. In urban and modified catchments, Tc tends to vary with rainfall intensity, antecedent moisture, drainage connectivity, and imperviousness. Studies that considered event-specific or condition-specific Tc generally produced more realistic runoff simulations than those assuming a single constant Tc value. This finding is particularly important for watersheds undergoing rapid land-use change, where static parameterization may no longer reflect actual flow concentration behavior.

The third theme relates to the interaction between Tc, rainfall resolution, and catchment memory. Studies using radar input and artificial neural networks indicate that predictive skill improves when rainfall is represented over an input window that is hydrologically consistent with the effective Tc of the watershed. This suggests that Tc is closely linked not only to travel time but also to the temporal scale at which rainfall information becomes relevant for runoff prediction, including the influence of antecedent storage and delayed flow components.

The fourth theme concerns land-use change and natural rehabilitation. Increasing imperviousness tends to shorten Tc, intensify peak discharge, and increase flood risk for short-duration storms. Conversely, interventions that enhance storage, roughness, or flow retardation may lengthen travel time and flatten the hydrograph. This demonstrates that Tc should be updated when catchment conditions change and that scenario-based runoff studies should explicitly account for its potential variability.

The flow of article identification and selection is shown in Fig. 5 (PRISMA).

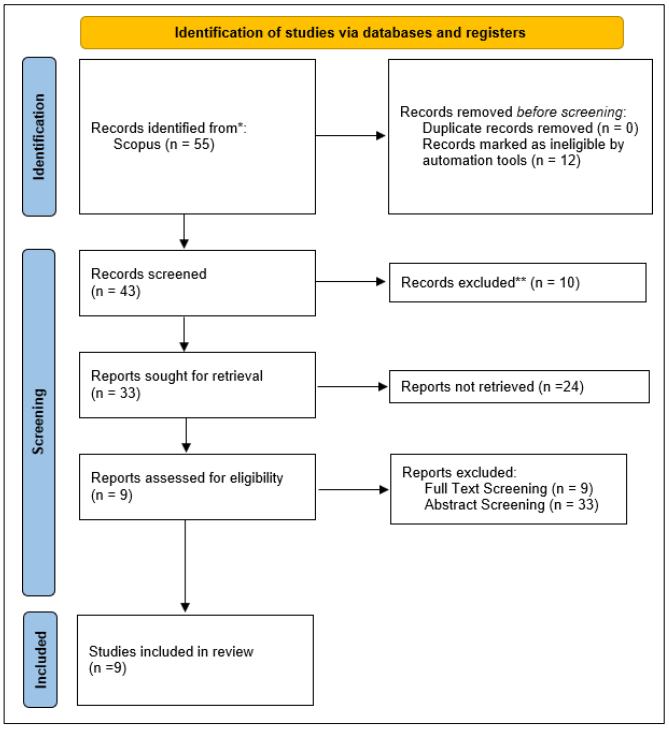

Fig. 5 - Identification of studies database

3.5 Search and selection results (PRISMA)

The PRISMA screening process began with 55 records identified through Scopus. After the removal of 12 records that were judged ineligible during the initial filtering stage, 43 articles remained for title and abstract screening. Ten articles were then excluded because they did not address Tc substantively in relation to runoff modelling, leaving 33 records for full-text retrieval. Due to access limitations, only 9 full-text articles were successfully assessed for eligibility, and all 9 satisfied the final inclusion criteria for qualitative synthesis. Although the final sample is relatively small, the selected studies provide focused evidence directly aligned with the review question.

The substantive characteristics and principal findings of the nine included studies are summarized in Table 1. The table functions as the analytical basis for the synthesis by linking study context, Tc treatment, modelling framework, and reported hydrological implications.

Table 1. Summary of reviewed studies on time of concentration and its influence on surface runoff modelling

No.	Author	Study Area	Method / Model	Key Variables	Main Findings
1	[13]	Iran	2D hydraulic simulation for Tc estimation	Tc, relative error	Hydraulic simulation outperformed most empirical equations and provided more reliable Tc estimates.
2	[2]	Catchment hydrology	Revisited Rational Formula	Peak discharge, runoff coefficient	Peak discharge estimation was extremely sensitive to both runoff coefficient and Tc assumptions.
3	[16]	Conceptual hydrology	Historical-conceptual review	Tc concept, celerity, response time	Tc should not be interpreted solely as particle travel time; catchment response is better explained by celerity and system dynamics.
4	[5]	Ungauged catchments, Iran	2D hydraulic simulation	Tc, benchmark deviation	The proposed approach showed strong agreement with benchmark methods and was dependable for ungauged basins.
5	[31]	Urban catchments, Saudi Arabia	Urban drainage design simulation	Discharge, velocity, lag time	Urban growth increased runoff coefficient, discharge, and velocity while reducing lag time, thereby intensifying drainage-design demands.
6	[17]	Kuala Lumpur, Malaysia	Comparative Tc evaluation	Tc, model reliability	Only a subset of empirical methods performed adequately, confirming that Tc equations are highly site dependent.
7	[32]	South African catchments	Comparative Tc estimation	Response time, peak discharge	Tc estimates varied widely across equations and strongly influenced peak discharge predictions.
8	[33]	Upper Po Basin, Italy	Comparative review of 24 Tc equations	Tc accuracy	No single equation was universally accurate, although several methods showed better performance across gauged catchments.

No.	Author	Study Area	Method / Model	Key Variables	Main Findings
9	[34]	30 Mediterranean basins (Italy, Greece, Cyprus)	GIS-based velocity method and varying Tc framework	Tc, runoff intensity, peak discharge, travel time	The study showed that Tc is not constant but decreases as excess rainfall intensity increases, supporting a varying-Tc concept in hydrological modelling.
10	[35]	Pervious overland flow surfaces	Full SWOF-PTM coupled with particle tracking method	Tc, runoff hydrograph, infiltration, rainfall intensity, slope, roughness, flow length	Tc on pervious surfaces was strongly controlled by infiltration, ponding time, rainfall intensity, slope, roughness, and flow length; the proposed equation outperformed Akan's equation.

A central discussion emerging from the literature is the strong influence of urbanization on Tc behavior. Increased imperviousness, more efficient drainage connectivity, and altered flow paths tend to shorten concentration time and accelerate runoff response. As a result, Tc values derived under earlier land-use conditions may become outdated as watershed morphology and drainage systems evolve. Periodic recalibration or re-estimation is therefore essential, especially in urban basins undergoing rapid development.

The review also demonstrates that variable Tc formulations are generally more informative than fixed Tc assumptions when the objective is to represent dynamic catchment response. Event-based variation in rainfall intensity, antecedent wetness, and land-use condition can alter effective travel time and, consequently, runoff generation. While fixed Tc remains useful for standardized design procedures, dynamic parameterization offers greater realism for simulation, scenario analysis, and adaptive flood-risk management.

Methodologically, the literature points toward an ongoing transition from simple empirical estimation toward integrated hydrological-hydraulic, spatially explicit, and data-driven modelling frameworks. Empirical equations remain valuable for quick applications and data-scarce contexts, but their limitations become more evident in highly urbanized or rapidly changing watersheds. By contrast, semi-empirical, hydraulic, and machine-learning-assisted approaches provide stronger capacity to represent temporal and spatial variability, although they also demand greater data quality and calibration effort.

From a practical perspective, these findings imply that Tc selection should be treated as a strategic modelling decision rather than a routine parameter choice. Urban drainage planning, stormwater infrastructure design, and flood-mitigation policy can be improved when Tc is updated in line with catchment change and when modelers explicitly justify whether a fixed or variable representation is more appropriate. In this sense, the role of Tc extends beyond runoff estimation to the broader question of model reliability for decision support.

Accordingly, the evidence reviewed suggests that future research should focus on integrating Tc estimation with real-time data sources, high-resolution rainfall products, and scenario-based urban development analysis. Such efforts would strengthen the capacity of surface runoff models to remain responsive under changing hydrological, climatic, and land-use conditions.

4. Conclusion

This systematic literature review confirms that time of concentration (Tc) is not merely a technical input, but a controlling parameter that shapes the structure, responsiveness, and predictive reliability of surface runoff models. According to the reviewed studies, differences in how Tc is defined, estimated, and implemented were shown to affect peak discharge prediction, hydrograph timing, and the delineation of flood-prone areas, particularly in urban catchments undergoing rapid land-use change. The findings therefore reinforce that Tc should be treated as a central modelling decision rather than a routine parameter assignment. The review further indicates that dynamic representations of Tc generally provide stronger hydrological realism than static formulations when runoff response is influenced by rainfall intensity, antecedent moisture, drainage connectivity, and changing surface imperviousness. At the same time, no single Tc approach is universally superior. Empirical equations remain useful for rapid screening and data-limited applications, whereas semi-physical, hydraulic, and integrated modelling approaches are more appropriate when the objective is to capture spatial heterogeneity, evolving catchment conditions, and event-scale runoff behavior. Accordingly, the selection of a Tc method should be aligned with catchment characteristics, data availability, model purpose, and the required level of predictive accuracy.

Overall, this review demonstrates that improving Tc representation can substantially strengthen the scientific robustness and practical relevance of surface runoff modelling. Future research should therefore prioritize uncertainty analysis, comparative testing across Tc formulations, and the integration of Tc estimation with high-resolution rainfall data, urban development scenarios, and real-time hydrological observations. Such directions are essential for developing runoff models that remain reliable, adaptable, and decision- relevant under increasingly dynamic environmental and urbanconditions.

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