

Distributed unit hydrograph (DUH) approach and mockus based analysis for hydraulic structure design in small watersheds under climate change conditions

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Abstract

In the Eastern Black Sea Region of Türkiye, streamflow gauging stations (AGS) are generally sparse and widely spaced in small watersheds; therefore, Synthetic Unit Hydrograph (SUH) methods are widely used for design discharge estimation. In particular, the Mockus (SCS) method is commonly adopted as the primary approach for hydraulic structure design in small and fast responding basins. However, under global warming conditions, the increasing frequency of short duration, high intensity rainfall events alters flood hydrograph characteristics, resulting in earlier peak times and higher peak discharges. In this study, the Altıntaş Stream watershed located in Rize, Türkiye, was considered as a representative small and steep basin of the Eastern Black Sea Region. In the first stage, SUH methods commonly used in Türkiye (Mockus, DSİ Synthetic, and Snyder) were applied, and the resulting hydrographs were analyzed. Based on this analysis, the limitations of these methods in representing physical processes, particularly in small and fast responding watersheds, were identified, and the necessity of examining the Distributed Unit Hydrograph (DUH) approach was justified within the preliminary analysis. Within this framework, a potential DUH scenario was developed based on literature findings, and a comparative analysis was carried out using a Mockus based DUH approach. The results indicate that SUH methods tend to underestimate peak discharge, delay the time to peak, and fail to adequately represent post flood processes, whereas the DUH approach provides earlier and higher peak discharges along with a more realistic representation of hydrograph behavior. These findings highlight the importance of the DUH approach for hydraulic structure design and operation in small watersheds.

Keywords: Hydraulic structure design, Flood hydrograph, Distributed unit hydrograph (DUH), Synthetic unit hydrograph (SUH), Design discharge, Climate change

1. Introduction

Global studies indicate that the frequency and intensity of short duration, high intensity convective precipitation have increased under climate change conditions (Prein et al., 2017; IPCC, 2021). Rising air temperatures lead to the temporal concentration of rainfall, resulting in faster hydrological responses and higher peak discharges, particularly in small and steep watersheds. This situation weakens the validity of classical assumptions regarding flood hydrograph characteristics such as shape, peak discharge, and time to peak and raises important concerns about the adequacy of Synthetic Unit Hydrographs (SUH) used in hydraulic structure design under global warming conditions.

In Türkiye and worldwide, streamflow gauging stations are generally located in medium and large watersheds, while observed flow data are often insufficient for small catchments. Therefore, Synthetic Unit Hydrograph (SUH) methods are widely used for estimating flood discharges in small and fast responding basins (Sivapalan et al., 2003; Blöschl et al., 2013). In particular, the DSİ Synthetic Unit Hydrograph method, along with the Mockus (SCS) and Snyder unit hydrographs, has long been applied as a standard approach in the design of many hydraulic structures in Türkiye.

However, synthetic unit hydrograph methods cannot directly represent the spatial variability of rainfall over the basin, infiltration and saturation processes, travel time delays along flow paths, or the effects of topography. Previous studies have shown that, especially under short duration and high intensity rainfall conditions, hydrographs derived from distributed approaches may produce higher peak discharges compared to synthetic methods (Beven, 2012; Merz et al., 2014; Kundzewicz et al., 2020). These findings suggest that design

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approaches based solely on conventional synthetic hydrographs may be insufficient for ensuring hydraulic safety under climate change conditions.

The Distributed Unit Hydrograph (DUH) approach represents the rainfall runoff process at the subbasin or grid scale and describes the rising and recession limbs, peak discharge, and time to peak of the hydrograph on a more physically based framework. In this respect, comparing DUH with SUH methods under climate change conditions appears important for evaluating their implications for hydraulic structure design.

The Altıntaş Stream Basin, considered in this study, is located in the Eastern Black Sea Region and is characterized by its small size and rapid hydrological response. The study area, located in Rize Province, exhibits high sensitivity to flash floods due to its topographic, hydrological, and climatic characteristics. The region is one of the areas in Türkiye where flood damages occur most frequently and severely, particularly under short duration, high intensity rainfall events that generate rapid surface runoff (Türkeş, 2010; Kadioğlu, 2012; Merz et al., 2014; Öztürk et al., 2015; Viglione et al., 2016). The basin represents a typical example of small catchments with insufficient streamflow observations. Its steep slopes, high humidity conditions, and short flow paths cause rainfall to be converted into runoff within a very short time. These characteristics make the Altıntaş Stream Basin a system with high flood potential and a representative case study area for the comparative evaluation of unit hydrograph approaches under climate change conditions.

In this study, the Altıntaş Stream watershed was evaluated in terms of the impacts of short duration, high intensity rainfall events expected to increase under global warming conditions. In the first stage, Synthetic Unit Hydrograph (SUH) methods commonly used in Türkiye (Mockus, DSİ Synthetic, and Snyder) were individually analyzed, and their hydrograph characteristics were evaluated. Based on this preliminary analysis, the limitations of these methods in representing flood behavior were identified, and the necessity of the Distributed Unit Hydrograph (DUH) approach was established.

Subsequently, the Mockus method, which is used as the primary approach for determining design discharge in small watersheds, was taken as the basis, and a literature based DUH approach was developed. The comparative analysis was then carried out within this framework. The main objectives of the study are as follows:

- (i) to evaluate the adequacy of synthetic unit hydrograph methods widely used in Türkiye under climate change conditions,
- (ii) to determine the effects of the DUH approach on peak discharge, time to peak, and hydrograph shape, and
- (iii) to provide an assessment of the most appropriate unit hydrograph approach for hydraulic structure design under changing climate conditions.

2. Material and method

The Altıntaş Stream watershed examined in this study is located in Rize Province in the Eastern Black Sea Region of Türkiye. The watershed was included in the implementation program by the General Directorate of State Hydraulic Works (DSİ) in 2006, and the construction works have been completed. The data used in this study were obtained from the Büyükköy Stream reconnaissance report prepared by DSİ

The methodology of this study is structured in three main stages: in the first stage, the morphometric, hydraulic, and hydrological characteristics of the watershed were evaluated, and Synthetic Unit Hydrograph (SUH) methods were examined within the context of global warming, through which the necessity of the Distributed Unit Hydrograph (DUH) approach was established; in the second stage, SUH diagrams were derived; and in the final stage, a comparative graphical analysis between SUH and DUH was carried out based on the Mockus method, which is used for determining design discharge in small watershed hydraulic projects.

2.1. Preliminary Assessment of Watershed Characteristics

In the preliminary analysis, the watershed characteristics of the study are including slope, rainfall, humidity, soil and geological properties, land use and infiltration characteristics, and hydrological conditions are evaluated under potential scenarios associated with extreme rainfall events intensified by global warming. The

adequacy of synthetic unit hydrograph methods under these conditions is examined as a preliminary assessment, supported by the relevant literature. Figure 1 shows the location of the Altıntaş Stream watershed within the Eastern Black Sea Region. The watershed parameters used in this study were obtained from the DSİ (2006) report, and no GIS based delineation was performed. The watershed parameters of the Altıntaş Stream are presented in Table 1.

The CN value used in this study was obtained from the DSİ (2006) reconnaissance report, where it was determined based on land use and soil characteristics using the SCS (CN) method. Since the objective of this study is not to rederive watershed parameters but to evaluate hydrograph behavior, the CN value was directly adopted without recalculation.

Table 1. Watershed parameters of the Altıntaş Stream (DSİ, 2006)

A (km ²) (derived from relevant maps)	7.2
L(km) main channel length	5.1
Lc(km) distance from the watershed centroid to the outlet section	2.5
H (m)Elevation difference	750
CN (selected for saturated soil conditions based on curve number tables corresponding to land use characteristics)	75
S (harmonic slope)	0.148

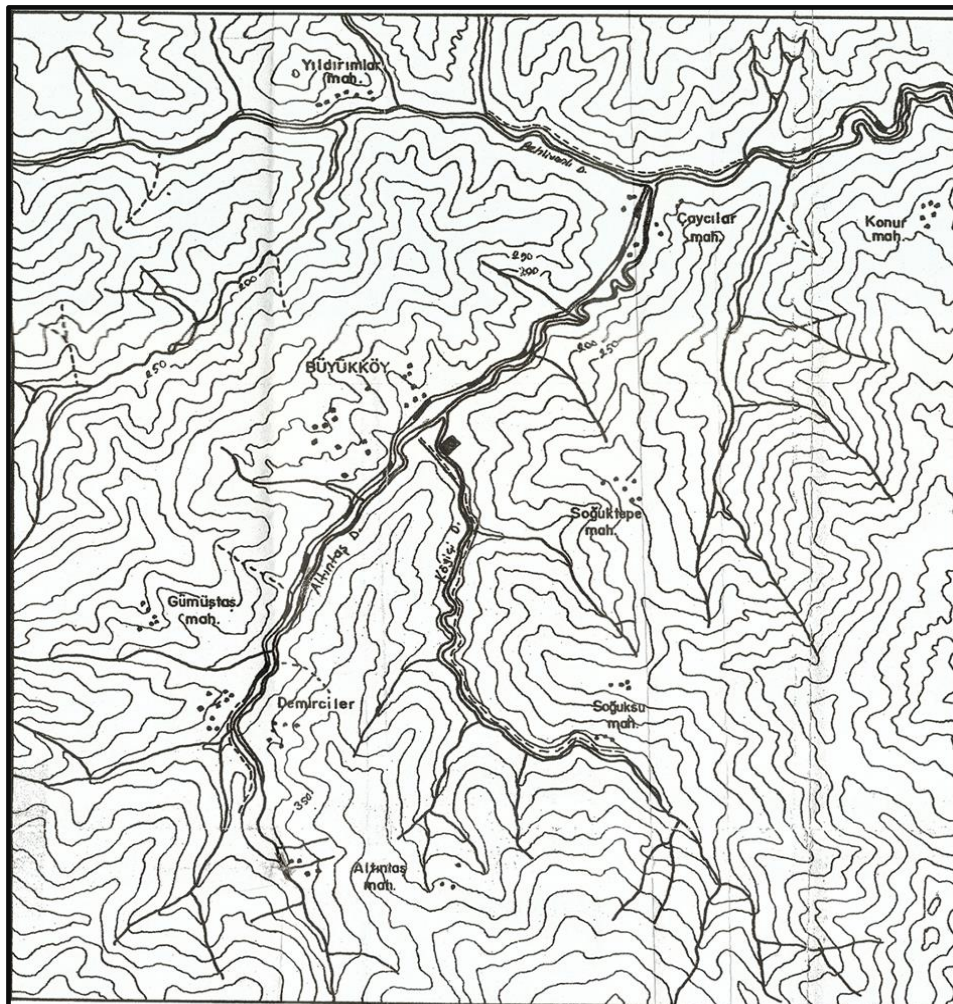


Figure 1. Location map of the study area (DSİ, 2006)

2.2. Evaluation of SUH diagrams under climate change conditions and examination of the DUH approach

In the first stage, the SUH hydrographs of the watershed were derived using the Mockus (SCS), DSİ Synthetic, and Snyder methods, respectively; and the main hydrograph parameters for each method, including peak

discharge (Q_p), time to peak (T_p), time of concentration (T_c), and recession time (T_r), were calculated. Appendix 1 and Appendix 2 present the calculation methods used for determining the SUH parameters, as well as the criteria for selecting the C_p and C_t coefficients of the Snyder method (Maidment, 1993; Kadioğlu, 2012; Wasko & Sharma, 2017).

In the Mockus (SCS) method, the rising limb of the hydrograph is assumed to vary linearly in order to represent the rapid response of the watershed outlet to rainfall. The peak of the hydrograph is defined based on the time of concentration (T_c) and unit discharge (q_u) values, while the recession limb is also drawn under a linear assumption, thereby reducing the hydrograph to a triangular form (Mockus, 1957; DSİ, 2006).

As presented in Appendix 3, in the DSİ Synthetic Unit Hydrograph method, the unit peak discharge (q_p) is determined using DSİ developed graphical relationships based on watershed area (A) and the $L \cdot L_c / S^{0.5}$ parameter (DSİ, 2006).

As given in Appendix 4, the Snyder Unit Hydrograph is constructed using the hydrograph widths at 50% (W_{50}) and 75% (W_{75}) of the peak discharge, measured on the recession limb. The W_{50} and W_{75} values are obtained from empirical relationships as a function of watershed area and are used together with the peak discharge (Q_p) to define the shape of the unit hydrograph (Snyder, 1938; DSİ, 1985).

In this study, the numerical DUH scenario parameters (T_c , D , T_p , Q_p , T_r , and total duration T) were defined based on findings in the literature indicating that distributed approaches tend to produce shorter response times and higher peak discharges than synthetic methods in small, steep, and fast responding watersheds. In this context, it was assumed that spatial rainfall variability and short flow paths accelerate the rising limb; therefore, T_c and T_p may decrease by approximately 15–25%, whereas T_r and the total hydrograph duration (T) may increase due to a more physically realistic representation of storage effects and delayed contributions along the recession limb. In addition, considering the literature based evidence that distributed/DUH approaches may increase peak discharge by approximately 30–40% in small watersheds, a 35% peak discharge increase scenario was adopted for the study area. The resulting DUH parameter ranges were established in line with classical hydrology references describing hydrograph theory and distributed modeling principles (Chow et al., 1988; Maidment, 1993), studies highlighting the effects of distributed rainfall runoff modeling in small basins (Ogden & Julien, 1994; Beven & Freer, 2001; Beven, 2012), and recent findings on accelerated flood response under climate change conditions (Del Río et al., 2020). In the evaluation of the diagram data, the diagram parameters presented in Appendix 5 were taken into consideration. Table 2 and Appendix 5 were used as references in the comparative analysis to highlight the process based differences between the SUH and DUH approaches and to interpret the variations in the rising and recession limbs of the hydrograph.

Table 2. Parameters within the scope of rising and recession limbs

Hydrograph Curves	Beginning and end of the curve	Parameters Affecting the Curve
Rising curve	AB curve	Basin Characteristics; Drainage Conditions and Slope
Recession curve	BD curve	Depletion processes related to groundwater, subsurface flow, and surface storage It is not related to rain fall or storm conditions

In the subsequent stage of the study, the comparative analysis between the SUH and DUH hydrographs was carried out by taking into account the process based differences presented in Table 3. The fundamental hydrological processes summarized in the table such as basin representation, spatial and temporal distribution of rainfall, flow path lengths, within basin delays, channel storage, and soil moisture conditions were evaluated in terms of their effects on the hydrograph parameters (Q_p , T_p , T_r , and T).

Within this framework, the hydrographs derived from the SUH and DUH approaches were compared with respect to the slope of the rising limb, time to peak, peak discharge magnitude, and recession limb duration. The observed differences were then interpreted by linking them to the process based mechanisms outlined in Table 3. Consequently, the analysis was not limited to a numerical comparison of results but was instead conducted through an assessment of the physical processes controlling hydrograph formation.

Table 3. Literature based conceptual comparison of SUH (Synthetic Unit Hydrograph) and DUH (Distributed Unit Hydrograph) approaches

Factor / Process	Representation / effect in the SUH (lumped synthetic UH) approach	Representation / effect in the DUH (distributed UH) approach	Expected difference in the hydrograph (Q_p , T_p , T_r , T)	Literature
Basin representation (model structure)	The basin is treated as a single homogeneous system; parameters are averaged over the entire watershed.	The basin is subdivided into sub areas/grid cells, and spatiotemporal variability is taken into account.	DUH: higher Q_p , shorter T_p , longer T_r , longer T ; SUH: a more “averaged” response.	Chow et al. (1988); Maidment (1993); Beven (2012)
Spatial distribution of rain fall	Rainfall is generally assumed to be uniform or represented by a basin average value.	Spatial rainfall heterogeneity and varying intensities over sub areas are taken into account.	DUH: the peak may increase ($Q_p \uparrow$) and hydrograph asymmetry may become more pronounced; SUH: the peak may be attenuated.	Maidment (1993); Beven (2012)
Temporal concentration of rain fall (short duration extreme rain fall)	Due to the assumption of averaged rainfall, run off may be distributed over time.	The rapid runoff generation triggered by short duration, high intensity rain fall is captured more effectively.	DUH: shorter T_p , higher Q_p ; SUH: the response may be delayed (longer T_p).	Merz et al. (2014); Blöschl et al. (2017); Wasko & Sharma (2017)
Flow-path lengths and travel time distribution	It is represented by a single average lag time / time of concentration.	The different travel times of each sub area are reflected in the hydrograph.	DUH: a steeper rising limb and a longer recession limb ($T_r \uparrow$, $T \uparrow$).	Rodríguez-Iturbe & Valdés (1979); Maidment (1993)
Representation of within-basin delays	Delays are assumed to be homogeneous; internal storage processes are simplified.	Sub area based delays and storage processes are represented in a more physically realistic manner.	DUH: a more realistic and longer recession ($T_r \uparrow$, $T \uparrow$).	Singh (1988); Maidment (1993); Beven & Freer (2001)
Channel storage and routing	Most SUH approaches rely on simplified hydrograph shape assumptions.	Channel storage and delayed drainage are reflected more consistently.	DUH: the tail effect becomes more pronounced ($T \uparrow$).	Chow et al. (1988); Singh (1988); Maidment (1993)
Soil moisture (AMC) and saturated areas	It is indirectly represented using a single basin average CN/AMC assumption.	Saturated areas and the spatial distribution of soil moisture are represented more realistically.	DUH: higher Q_p , shorter T_p , longer T_r ; SUH: more symmetric/simplified.	Chow et al. (1988); Maidment (1993); Beven & Freer (2001); Beven (2012)

2.3. Mockus-based comparative analysis of SUH and DUH in the design process of small watersheds

In this section, the SUH and DUH approaches are comparatively evaluated based on the Mockus method, which is used as the primary approach for determining design discharge in small watershed hydraulic design practices. In engineering applications in Türkiye, particularly in small and fast responding watersheds, design discharge is commonly determined using the Mockus (SCS) method. Therefore, the comparative analysis was structured not as a purely theoretical comparison of methods, but in a way that reflects real engineering practice by taking the Mockus hydrograph as the reference condition.

Within this framework, the SUH Mockus hydrograph and the literature based DUH approach were compared graphically in terms of rising limb slope, time to peak (T_p), peak discharge (Q_p), and recession limb behavior. The observed differences were evaluated in the context of changing flood behavior under global warming conditions in small and fast responding watersheds, and their implications for hydraulic structure design were discussed.

3. Result and discussion

3.1. Preliminary assessment of watershed characteristics

When the watershed parameters of the study area are evaluated collectively, it is clearly evident that this watershed, located in the Eastern Black Sea Region, exhibits a high sensitivity to flooding under extreme rainfall events intensified by global warming.

The small watershed area of 7.4 km² leads to a very rapid rainfall runoff response. In small watersheds, storage capacity is limited, and a large portion of rainfall is transformed into surface runoff within a short time. This condition creates a strong tendency for sudden and high flood peaks, particularly under the increasing frequency of short duration, high intensity rainfall events associated with climate change.

The main channel length of 5.5 km and the distance from the watershed centroid to the outlet of 2.5 km indicate short flow paths and a low watershed lag time. Under global warming conditions, the shortening of convective rainfall duration combined with increased rainfall intensity causes flood peaks to occur earlier due to these short travel distances.

The elevation difference of 750 m and the high harmonic slope value of 0.174 indicate a high potential energy component and rapid increases in flow velocity. This topographic structure promotes rapid runoff concentration and results in a steeper rising limb of the hydrograph. With climate change induced increases in short duration rainfall intensity, flood responses under such steep slope conditions become even more abrupt. The CN value of 75, determined based on land use and soil characteristics, suggests a moderate infiltration capacity; however, under saturated soil conditions the watershed becomes highly prone to surface runoff. In the Eastern Black Sea Region, high humidity and frequent rainfall lead to rapid soil saturation, increasing effective rainfall during successive storm events and amplifying flood risk.

The maximum elevation of 960 m reflects pronounced orographic effects and indicates that rainfall is not spatially homogeneous across the watershed. Under global warming conditions, increased rainfall intensity in watersheds with significant elevation gradients further enhances the temporal concentration of runoff.

In conclusion, when the small watershed area, steep slopes, short flow paths, limited infiltration capacity, and humid climatic conditions are considered together, this Eastern Black Sea watershed exhibits a hydrological response characterized by early peak occurrence, high peak discharge, and a strong tendency toward flash flooding under extreme rainfall scenarios intensified by global warming.

The Altıntaş Stream Watershed exhibits a hydrological structure that is highly sensitive to flash floods due to its small drainage area, high average slope, short flow paths, and pronounced orographic effects. In such watersheds, surface runoff develops very rapidly, and the basin response becomes temporally concentrated. This behavior contradicts the fundamental assumptions of synthetic unit hydrograph (SUH) methods, which rely on homogeneous rainfall and average basin response (Chow et al., 1988; Ogden & Julien, 1994; Beven, 2012).

In the Eastern Black Sea Region, the spatial distribution of rainfall varies significantly, particularly due to differences in elevation. Short duration, high intensity convective rainfall events produce asynchronous and heterogeneous flow responses across different parts of the watershed. Under global warming conditions, the increased frequency and intensity of such events further limit the ability of the fixed time and shape parameters used in SUH methods to accurately represent flood behavior (Merz et al., 2014; Blöschl et al., 2017; Wasko & Sharma, 2017).

In this context, the Altıntaş Stream Watershed provides a suitable and representative study area to demonstrate the differences between SUH and DUH approaches under global warming conditions, to evaluate the limitations of synthetic methods, and to assess the superiority of distributed approaches in representing flood hydrographs.

3.2. Evaluation of SUH diagrams under climate change conditions and examination of the DUH approach

Table 4 presents the numerical values of key hydrograph parameters obtained for the Altıntaş Stream Watershed using different synthetic unit hydrograph (SUH) methods. These parameters define the characteristic features of the hydrograph, including peak discharge (Q_p), time to peak (T_p), time of concentration (T_c), rising and recession limb durations (D , T_r), and total flood duration (T).

Table 4. Numerical values of SUH parameters for the Altıntaş watershed

Altıntaş Stream Flood Hydrology (Mockus Method)	Results	DSİ Synthetic Method	Results	Snyder	Results
Tc	0,48	Hp	33,14	tp	2,90
D	1,38 (2h)				
Tp	1,29	qp	151,65	tr	0,53
Qp (m ³ /sn/mm)	0,83	Tp	1,34	qp	517,1
T R(h)	2,15	Qp	1,09	Qp	0,41
T	3,43			Tp	3

Table 5 provides a comparative summary of hydrograph parameters obtained for the Altıntaş Stream Watershed using different synthetic unit hydrograph (SUH) methods and a literature based potential Distributed Unit Hydrograph (DUH) scenario. The table presents the numerical values and relationships of key hydrograph characteristics, including time of concentration (Tc), effective rainfall duration (D), time to peak (Tp), peak discharge (Qp), recession limb duration (Tr), and total flood duration (T), highlighting the differences between SUH and DUH approaches.

In the literature, it is widely reported that distributed hydrograph approaches tend to produce higher peak discharges than synthetic (lumped) unit hydrograph (SUH) methods. Although the magnitude of this difference varies depending on watershed scale, topographic characteristics, and the temporal spatial structure of rainfall, it becomes particularly pronounced in small and heterogeneous catchments.

[Del Río et al. \(2020\)](#) demonstrated that in small and heterogeneous watersheds with short time of concentration (Tc), distributed approaches generate approximately 30–40% higher peak discharges than synthetic unit hydrograph methods such as SCS (Mockus) and Snyder. This increase mainly results from the more realistic representation of rainfall spatial heterogeneity and short flow paths in distributed modeling frameworks.

[Beven \(1988, 2012\)](#) emphasized that synthetic unit hydrograph methods tend to over disperse watershed response in time, whereas distributed approaches concentrate runoff temporally, leading to higher peak discharge (Qp) values and shorter time to peak (Tp). This difference arises from the fact that lumped SUH methods represent physical processes through spatially averaged assumptions.

[Ogden and Julien \(1994\)](#) showed that in watersheds characterized by short flow paths and steep slopes, distributed models produce earlier and higher peak discharges compared to synthetic approaches. This finding indicates that lumped methods may systematically suppress peak discharge in mountainous and rapidly responding basins.

Studies conducted in the context of global climate change also support this tendency. [Merz et al. \(2014\)](#) and [Blöschl et al. \(2017\)](#) noted that the increasing occurrence of short duration, high intensity rainfall events can cause lumped synthetic unit hydrograph approaches to underestimate peak discharge, making the discrepancy between distributed and synthetic methods even more evident under climate change conditions.

While Synthetic Unit Hydrograph (SUH) methods describe rainfall and runoff using basin averaged parameters, the Distributed Unit Hydrograph (DUH) approach explicitly accounts for the spatial and temporal variability of precipitation and flow processes. This fundamental difference leads to significant deviations in key design parameters such as peak discharge magnitude and time to peak that directly influence the design of hydraulic structures.

The literature widely reports that, particularly in small and heterogeneous catchments, DUH based approaches tend to produce earlier peak times and peak discharges that are approximately 30–40% higher compared to those obtained using SUH methods ([Beven, 1988](#); [Del Río et al., 2020](#)).

Taken together, these findings suggest that distributed unit hydrograph approaches are expected to yield 30–40% higher peak discharges than synthetic methods. In this study, considering that the study watershed is characterized by a small drainage area, steep topography, short flow paths, and humid climatic conditions, a 35% peak discharge increase was adopted to represent DUH behavior. This selected value lies within the mid to upper range of the interval reported in the literature and was preferred to reflect the influence of short

duration and high intensity rainfall events under global warming conditions. The Table 5 presents the numerical SUH results and, based on the watershed characteristics of the study area and the supporting literature, summarizes the corresponding increase/decrease ratios, curve properties, and hydrograph recession behavior.

Table 5. Literature-based SUH and DUH diagram values and characteristics

Parameter	Mockus Method	DSI Synthetic Method	Snyder Method	Potential Mockus-DUH data	DUH (Literature-based)	Explanation related to numerical data
Tc (h)	0,48	-	-	0,38	0,36 – 0,40	20% decrease in local delays
D (h)	1,38	-	-	1,25	1,2 – 1,3	Shorter effective rainfall duration
Tp (h)	1,29	1,34	3,00	1,00	0,95-1,10	15–25% reduction in short flow paths
Qp (m ³ /s/mm)	0,83	1,09	0,41	1,13	1,12-1,15	35% increase (30–40%), temporal concentration
Tr (h)	2,15	-	0,53	2,65	2,5-3,00	Prolonged recession limb and increased non-linear recession behavior
T (h) Total duration	3,43	-	-	3,65	3,6-4,00	Tail effect and an extended tail ≈ or ↑

Moreover, the DUH and SUH percentage differences reported in the literature are not specific to a single synthetic unit hydrograph method; rather, they refer broadly to all lumped synthetic unit hydrograph approaches, including SCS (Mockus), Snyder, and similar methods (Beven, 1988; Chow et al., 1988; Ogden & Julien, 1994; Beven & Freer, 2001; Del Río et al., 2020).

As shown in Figure 2, the diagram compares the peak discharge (Qp, m³/s/mm) values obtained for the Altıntaş Stream Watershed using different synthetic unit hydrograph (SUH) methods and a potential Mockus DUH scenario. Accordingly, the Mockus method provides a baseline value of 0.83 m³/s/mm, while the DSI Synthetic method yields a Qp of 1.09 m³/s/mm, approximately 31% higher than the Mockus value. The Snyder method produces a Qp of 0.41 m³/s/mm, about 51% lower than Mockus and distinctly different from the other methods. In the potential Mockus DUH scenario, Qp is 1.13 m³/s/mm, representing an increase of approximately 35 % compared to the Mockus method

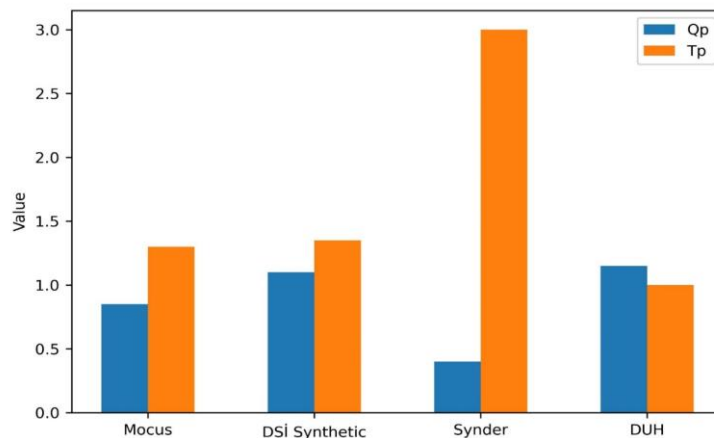


Figure 2. Comparison of SUH and (% 35 probable unit hydrograph) Mockus based DUH

Figure 3 presents the Mockus synthetic unit hydrograph. The hydrograph obtained using the Mockus method exhibits a triangular structure characterized by linear rising and linear recession limbs. In this approach, the peak discharge occurs near the geometric center of the hydrograph, and an almost symmetric behavior is observed between the rising and falling limbs. However, this linear structure fails to physically represent the post peak recession process and the contribution of baseflow. Consequently, the Mockus hydrograph presents the flood duration and discharge variations around the peak within a highly simplified framework (Mockus, 1957; Chow et al., 1988; Singh, 1988).

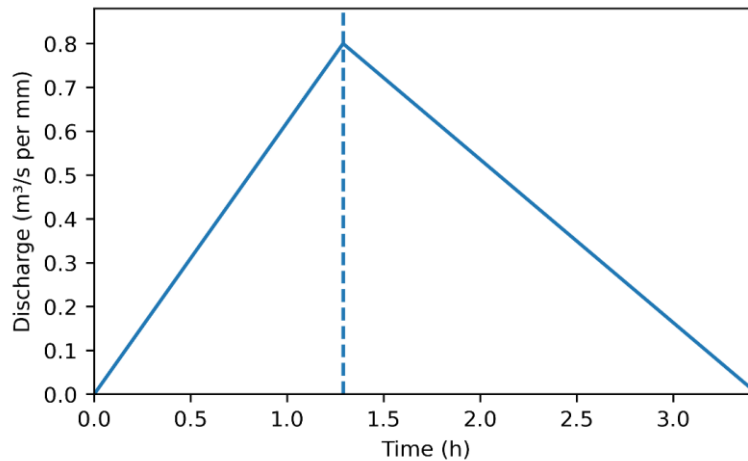


Figure 3. Mockus unit hydrograph of the Altıntaş stream

In this study, the value of K used for the Altıntaş Stream watershed is one of the key parameters directly controlling the watershed response time. The relatively low K value causes the hydrograph to reach its peak more rapidly and leads to a temporal concentration of flood volume within a shorter duration. However, due to the triangular and linear structure of the Mockus method, this effect does not allow for a realistic representation of abrupt changes around the peak discharge or the recession process (Mockus, 1957; Özdemir, 1978).

Considering the small drainage area, steep topography, and short flow paths of the Altıntaş Stream watershed, a low K value would theoretically be expected to reflect a rapid flood response. Nevertheless, owing to the structural assumptions of the method, the post peak flow attenuation is modeled faster than physically realistic, while baseflow and delayed surface runoff components are neglected. Previous studies have emphasized that, particularly in mountainous and rapidly responding watersheds, the Mockus method inadequately represents the recession limb and therefore underestimates flood duration (Chow et al., 1988; Maidment, 1993; Beven, 2012).

When evaluated in the context of global warming, the increasing occurrence of short duration, high intensity precipitation events results in higher peak discharges and more complex recession behavior. Under such conditions, the assumption of a linear hydrograph governed by a fixed K coefficient proves insufficient to represent the temporal asymmetry of the rainfall runoff process and delayed flow components. Recent studies indicate that the inability of the Mockus method to capture prolonged post flood recession behavior has become increasingly evident under changing climatic conditions (Merz et al., 2014; Blöschl et al., 2017; Wasko & Sharma, 2017).

In summary, although a K value theoretically indicates a rapid hydrological response for the Altıntaş Stream watershed, the linear and triangular structure of the Mockus method fails to adequately represent abrupt variations around the peak discharge, the extended recession limb, and the increasing flood complexity associated with global warming. This limitation highlights why Distributed Unit Hydrograph (DUH) approaches, which explicitly account for the spatial and temporal variability of rainfall, provide more reliable results, particularly in small and steep watersheds (Beven & Freer, 2001; Beven, 2012).

Figure 4 presents the DSI synthetic unit hydrograph. This figure presents a comparison between a dimensionless synthetic hydrograph ($T/T_p - Q/Q_p$) and an observed (or physically representative) hydrograph ($T-Q$).

As clearly shown in the figure, the dimensionless hydrograph reaches its peak at an earlier normalized time and exhibits a rapid recession immediately after the peak. In contrast, the observed hydrograph displays a more gradual and prolonged recession limb, indicating that floodwaters persist in the system for a longer duration. This difference highlights the inability of synthetic, dimensionless hydrograph formulations to adequately represent delayed runoff components such as interflow, subsurface flow, and baseflow contributions.

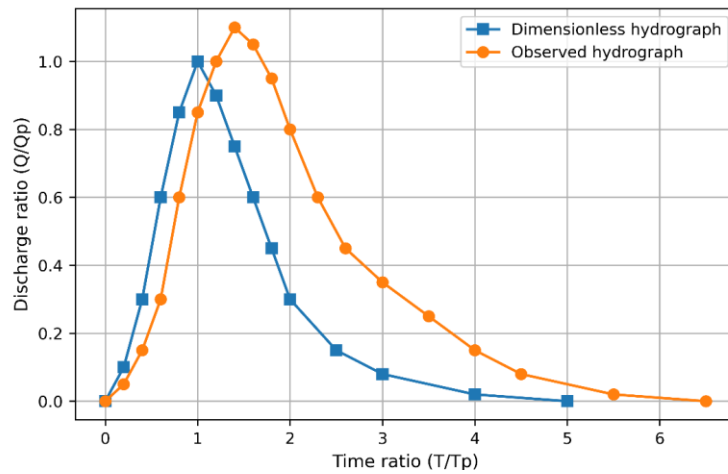


Figure 4. DSI synthetic unit hydrograph of the Altıntaş stream

Under global warming conditions, the increasing frequency of short duration, high intensity precipitation events leads to sharper rising limbs, higher peak discharges, and more complex post peak flow dynamics, particularly in small and steep watersheds. However, synthetic unit hydrograph approaches rely on fixed, idealized shapes and assume homogeneous rainfall and linear watershed response. As a result, these methods tend to oversimplify the recession behavior and underestimate the temporal extent of flood impacts.

The comparison illustrated in this figure demonstrates that, when synthetic or dimensionless hydrographs are used under changing climatic conditions, flood duration and post peak effects are likely to be underestimated, even if peak discharge magnitude appears reasonable. In contrast, observed or distributed hydrograph representations better capture the extended recession behavior and sustained hydraulic loading on water structures.

Consequently, this figure supports the conclusion that reliance on synthetic unit hydrograph methods alone may introduce hydraulic and operational risks in the design and operation of water structures under global warming conditions, further emphasizing the necessity of Distributed Unit Hydrograph (DUH) approaches that explicitly account for spatial rainfall variability and internal flow delays.

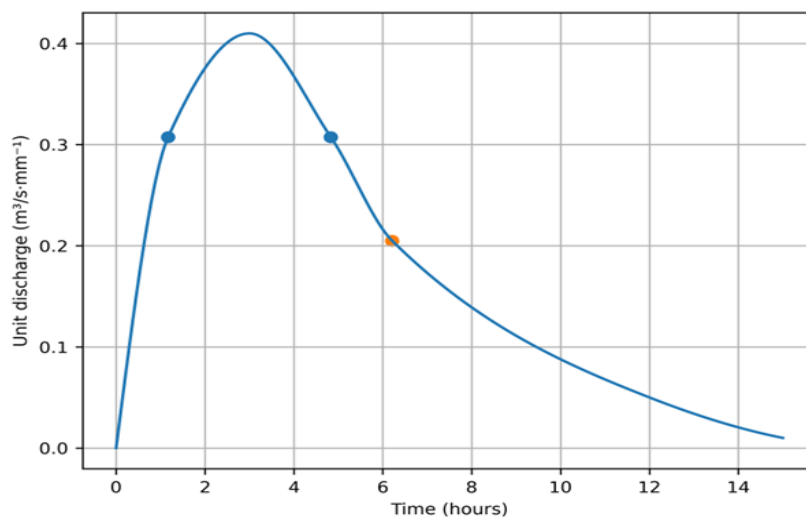


Figure 5. Snyder synthetic unit hydrograph of the Altıntaş stream

Figure 5 presents the Snyder unit hydrograph. The Snyder Synthetic Unit Hydrograph method applied in this study produces a more realistic and curvilinear hydrograph shape compared to the Mockus method. In particular, the drawing approach based on W50 and W75 widths ensures a smoother transition around the peak discharge and allows the recession limb to exhibit a longer and more gradual decay than triangular hydrographs (Snyder, 1938; Singh, 1988; Maidment, 1993).

However, the Snyder method treats the watershed response as a single lumped system and does not explicitly account for the spatial distribution of rainfall. The hydrograph shape and magnitude are primarily controlled by the empirically defined C_t (time coefficient) and C_p (peak discharge coefficient) parameters, which are assumed to be constant (Snyder, 1938; Özdemir, 1978; Chow et al., 1988).

The C_t value adopted in this study corresponds to a relatively longer watershed response time. Given the small drainage area, steep slopes, and short flow paths of the Altıntaş Stream watershed, this C_t value may cause the time to peak to be represented later than physically expected during short duration, high intensity storm events. Previous studies have noted that fixed C_t values are often insufficient to capture changing rainfall dynamics, particularly in mountainous watersheds affected by orographic precipitation (Chow et al., 1988; Ogden & Julien, 1994; Merz et al., 2014).

Similarly, the C_p value represents a moderate limitation on peak discharge magnitude. In watersheds such as Altıntaş Stream where runoff efficiency is high, saturation develops rapidly, and large discharges can occur within short periods this parameter choice may lead to underestimation of peak flows. The literature indicates that C_p is highly sensitive to rainfall intensity and saturation conditions, and that using a fixed coefficient introduces uncertainty in such hydrologically responsive systems (Singh, 1988; Maidment, 1993; Beven, 2012).

In this context, the combination of C_t and C_p within the Snyder method tends to produce a hydrograph that delays the time to peak while constraining peak discharge magnitude. Under global warming conditions characterized by increasingly frequent short duration, high intensity precipitation events this approach is unable to fully capture the rapid flood response typical of such systems (Türkeş, 2010; Merz et al., 2014; Prein et al., 2017; Wasko & Sharma, 2017).

In conclusion, although the Snyder Synthetic Unit Hydrograph method provides a more refined hydrograph geometry than the Mockus method, its lumped structure and reliance on fixed C_t and C_p parameters limit its ability to represent the temporal and spatial hydrological variability intensified by climate change. This limitation clearly demonstrates why Distributed Unit Hydrograph (DUH) approaches capable of explicitly accounting for spatial rainfall variability, internal flow delays, and heterogeneous surface conditions offer a more appropriate alternative for small, steep, and climate sensitive watersheds such as the Altıntaş Stream (Beven & Freer, 2001; Beven, 2012).

The hydrograph obtained using the DSİ Synthetic Unit Hydrograph method occupies an intermediate position between the Mockus and Snyder methods in terms of shape. While the rising limb exhibits a curvilinear character similar to the Snyder hydrograph, the recession limb is longer and more physically meaningful than that of the Mockus method. With its single peaked and asymmetric structure, the DSİ and SUH hydrograph reflects the characteristic features of the synthetic approach widely used in flood and regulator design projects in Türkiye.

In this context, the comparison among synthetic methods reveals how hydrograph shape is influenced by empirical assumptions, yet fails to fully represent the effects of complex topographic and climatic characteristics on watershed hydrological response.

When the three synthetic methods are evaluated together, their differences are observed to primarily concentrate on hydrograph shape and time related parameters. While peak discharge magnitudes remain within a similar range, peak times and the slopes of the rising and recession limbs vary depending on the method. However, since all methods rely on assumptions of homogeneous rainfall, average watershed response, and linear system behavior, these differences do not constitute a fundamental qualitative distinction in representing watershed hydrological dynamics.

Figure 6 presents the potential DUH diagram obtained based on the 35% scenario defined in the literature. The DUH based hydrograph clearly produces a higher peak discharge (Q_p) and reaches the time to peak (T_p) in a shorter period, indicating that runoff becomes temporally concentrated in the study basin and that the basin responds rapidly to rainfall. This behavior is closely associated with physiographic characteristics such as the small basin scale, steep topographic slopes, and short flow paths, which accelerate overland flow.

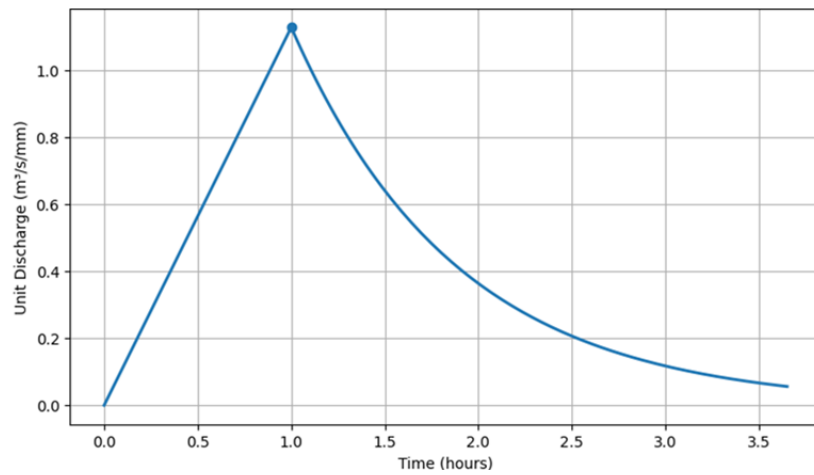


Figure 6. Possible DUH hydrograph

In contrast, the prolonged and nonlinear recession limb observed after the peak cannot be explained solely by a simple attenuation mechanism driven by surface runoff. Instead, it can be interpreted as the result of stored water within the basin contributing to the system over time. This pattern suggests a more realistic representation of delayed runoff components, including channel storage, interflow, shallow groundwater contribution, and the asynchronous (successive) contributions of different sub areas.

Moreover, the high Q_p values and the rapidly rising limb imply that antecedent moisture conditions (AMC) may be influential in the basin. As near saturated areas expand, infiltration capacity decreases, allowing a larger portion of effective rainfall to be converted into runoff within a short period. Overall, these findings demonstrate that distributed approaches can represent both the peak magnitude and the post peak recession process of flood hydrographs in a more physically meaningful manner compared to synthetic methods (Chow et al., 1988; Maidment, 1993; Ogden & Julien, 1994; Beven & Freer, 2001; Beven, 2012).

3.4. Mockus-based comparative DUH analysis for hydraulic structure design

In this section, the hydrograph behavior is evaluated based on the Mockus method and interpreted within the DUH framework for hydraulic structure design.

For the comparative diagram, the most appropriate method was first selected based on the procedures commonly used in Turkey for design discharge estimation. As shown in Table 6, studies conducted in Turkey indicate that, in small basin design applications, different methods may be applied depending on parameters such as basin area and time of concentration and rising time. Given that the study basin has an area of 7.4 km² and is characterized by a small size, steep slopes, and short flow paths, the Mockus method was determined to be the most suitable approach for this application.

Table 6. Synthetic and related parameters (Sönmez, 2017)

Drainage Area (km ²)	Method	Assembly and Rise Time
$A < 1$	Rational	-
$1 < A < 10$	Mockus	$T_c < 30 h$
10-1000	DSI Synthetic	$T_p \geq 2 h$
$A > 1000$	Snyder	-

In this context, as shown in Figure 7, the SUH and DUH results are graphically compared using the Mockus method. The comparative hydrograph diagram reveals distinct differences between the SUH Mockus triangular unit hydrograph and the DUH based flood response, particularly in terms of the rising limb, peak discharge, time to peak, and recession limb behavior. These differences clearly reflect the realistic hydrological response of small scale, steep slope, and spatially heterogeneous basins characteristic of the Eastern Black Sea Region under global warming conditions.

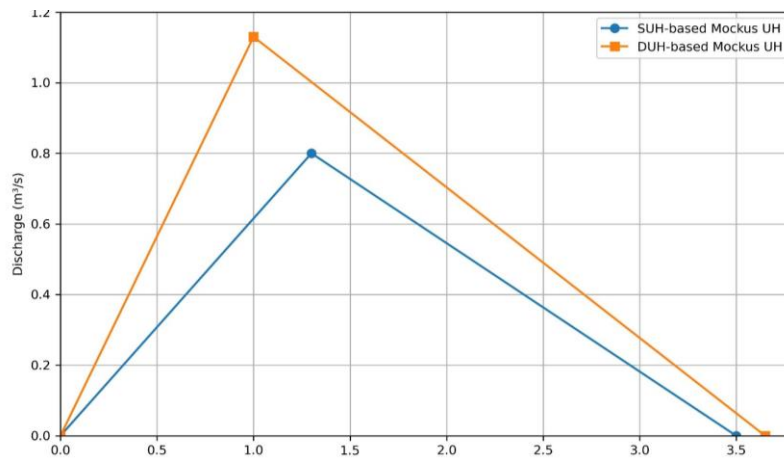


Figure 7. Comparative analysis of SUH (Mockus) and DUH based hydrographs

The comparisons conducted under global warming conditions in terms of the main hydrograph parameters rising limb behavior, peak discharge (Q_p) and time to peak (T_p), effective rainfall duration (D) and basin response, as well as recession limb and tail behavior can be summarized as follows:

Rising limb behavior: The DUH based hydrograph exhibits a much steeper rising limb compared to the SUH Mockus hydrograph. This indicates that surface runoff becomes rapidly concentrated due to short flow paths, high local slopes, and limited storage capacity within the basin. In contrast, the SUH Mockus approach spreads the basin response over time and suppresses the rate of discharge increase. Particularly under the Eastern Black Sea conditions, where short duration and high intensity rainfall events are dominant, the SUH approach represents the initial flood formation stage in a delayed and attenuated manner.

Peak discharge (Q_p) and time to peak (T_p): The DUH based hydrograph produces an earlier time to peak ($T_p = 1.00$ h) and a clearly higher peak discharge ($Q_p = 1.13$). This outcome results from the more realistic representation of spatiotemporal rainfall heterogeneity and short runoff pathways within distributed approaches. In contrast, the SUH Mockus method yields a later and lower peak, thereby systematically underestimating the true flood potential. Under global warming conditions, where rainfall intensity becomes more decisive than total rainfall amount, this discrepancy becomes even more critical.

Effective rainfall duration (D) and basin response: In the DUH approach, the use of a shorter effective rainfall duration ($D = 1.25$ h) causes the basin response to become more impulsive and concentrated. This behavior is consistent with the convective and orographic rainfall types frequently observed in the region. Conversely, SUH based methods rely on the assumption that rainfall is homogeneously distributed in space and time; therefore, they cannot adequately represent the flood generation mechanisms in small and rapidly responding basins.

Recession limb and tail behavior: Although the DUH based hydrograph generates a higher and earlier peak, it also exhibits a longer recession limb and an extended tail ($T = 3.65$ h). This pattern reflects the influence of delayed flow components under humid climatic conditions, including hillslope drainage, shallow subsurface flow, and temporary in channel storage processes. By assuming a linear and symmetric recession limb, the SUH Mockus hydrograph fails to sufficiently represent these physical processes.

Hydrological and engineering implications: As clearly observed in the diagram, the DUH based hydrograph produces a steeper rising limb, a higher peak discharge, and a longer duration of hydraulic loading. This indicates potential risks in designs based on the SUH Mockus method, such as insufficient spillway capacity, delayed operational maneuvers, and reduced safety margins in regulators and conveyance structures. Especially in basins of the Eastern Black Sea Region that generate floods within short time scales, these differences are of a magnitude that cannot be neglected in design practice.

Overall, the diagram explicitly demonstrates that the DUH approach provides a more critical flood behavior than SUH, directly affecting the design and operation of hydraulic structures:

- In DUH, the peak discharge is higher and occurs earlier (shorter T_p). This implies larger design discharges and a shorter response time requirement for spillways, regulators, conveyance channels, and flood control structures. SUH based designs may fail to capture this early and high peak, leading to the risk of undersized cross sections and insufficient capacity.
- In DUH, the recession limb is longer and attenuates more slowly. This indicates that structures may remain under high flow conditions for a longer period, increasing risks such as structural loading, scour, downstream impacts, and extended operational stress. In SUH, the shorter and more linear recession limb tends to underestimate these effects.
- From an operational perspective, the rapid rising limb and extended tail behavior indicated by DUH require more cautious and flexible operational strategies in terms of gate operations, sudden load changes in hydropower facilities, and downstream safety considerations.

4. Conclusions and recommendations

Under global warming conditions, particularly in small, steep, and fast responding watersheds in the Eastern Black Sea region, flood behavior resulting from short duration, high intensity rainfall cannot be adequately represented using classical Synthetic Unit Hydrograph (SUH) methods. Analyses conducted on the Altıntaş Stream and literature reviews have yielded the following findings:

DUH and SUH Comparison: The Distributed Unit Hydrograph (DUH) approach produces earlier time to peak (T_p), shorter time of concentration (T_c), and approximately 30–40% higher peak discharge (Q_p) compared to SUH methods.

Limitations of SUH Methods: SUH methods (Mockus, DSI Synthetic, Snyder) tend to temporally disperse watershed response, resulting in suppressed peak discharges and prolonged flood response times. Notably, the Snyder method produces excessively long T_p values for small watersheds. Although the Mockus method provides relatively more representative results among SUH approaches for small watersheds, it still fails to physically capture rapid peak behavior and recession limb dynamics.

Characteristics of the DUH Approach: DUH based hydrographs realistically represent both the rapid loading and persistent hydraulic effects of floods through their steep rising limbs, high peak discharges, and prolonged recession limbs. While DUH does not directly model small scale processes such as groundwater flows, soil moisture, low flows, or soil infiltration capacity, it sufficiently captures the overall flood hydrograph, including high peaks and rapid loading.

Relevance for Small Watersheds in Turkey: In Turkey, particularly for small watersheds, the sparse and often distant gauge network renders observational methods such as regional or AGI/SGIB approaches unreliable. Therefore, unit hydrograph methods must be appropriately selected in small and data scarce watersheds and used to estimate flood response and design discharges for hydraulic structures.

Design Discharge and Hydraulic Structures: Design discharges derived from SUH methods systematically produce lower values in terms of peak magnitude and timing, which reduces the safety margins of hydraulic structures. In small watersheds in Türkiye, the Mockus (SCS) method is directly adopted as the basis for determining project design discharge in engineering practice. Therefore, the comparisons in this study were carried out based on the Mockus method, and the DUH approach was evaluated within this framework.

DUH based numerical data should be used to reassess the design parameters of regulators, spillways, flood protection structures, conveyance channels, and energy facilities. Since the DUH approach represents rapid loading, higher peak discharges, and prolonged hydraulic effects, it is critical for the safe and economical design of hydraulic structures.

Institutional and Numerical Recommendations: The current data infrastructure and institutional regulations are not adequate for the effective application of the DUH approach. In Turkey, DUH based numerical modeling and a new data workflow and guideline framework should be developed at the institutional level for flood

design in small watersheds. Projects based on incomplete or inadequate methods may lead to significant flood risks and economic losses; therefore, previous SUH based projects should be reassessed using DUH.

In conclusion, the DUH approach represents flood behavior under global warming conditions with earlier peaks, higher discharges, and longer effective durations. The limitations of SUH methods under these conditions are not merely academic but constitute a real engineering problem directly affecting structural safety, operational risk, and economic losses. Therefore, strengthening the design processes of hydraulic structures in small watersheds in Turkey with DUH based numerical data and appropriate institutional regulations is imperative.

The findings of this study are not limited to the comparison of hydrograph methods but also provide important implications for the design and operation processes of hydraulic structures in small watersheds. The differences between the Mockus based analysis and the DUH approach were evaluated in terms of design discharge, hydrograph shape, and flood response, and their direct impacts on engineering applications were demonstrated. In this context, the results are expected to contribute to the determination of design and operational criteria for hydraulic structures in small watershed projects.

Declaration of ethical code

The author declares that the materials and methods employed in this study do not require approval from an ethics committee and/or any legal or special authorization.

Conflicts of interest

The author declares that there is no conflict of interest.

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APPENDICES

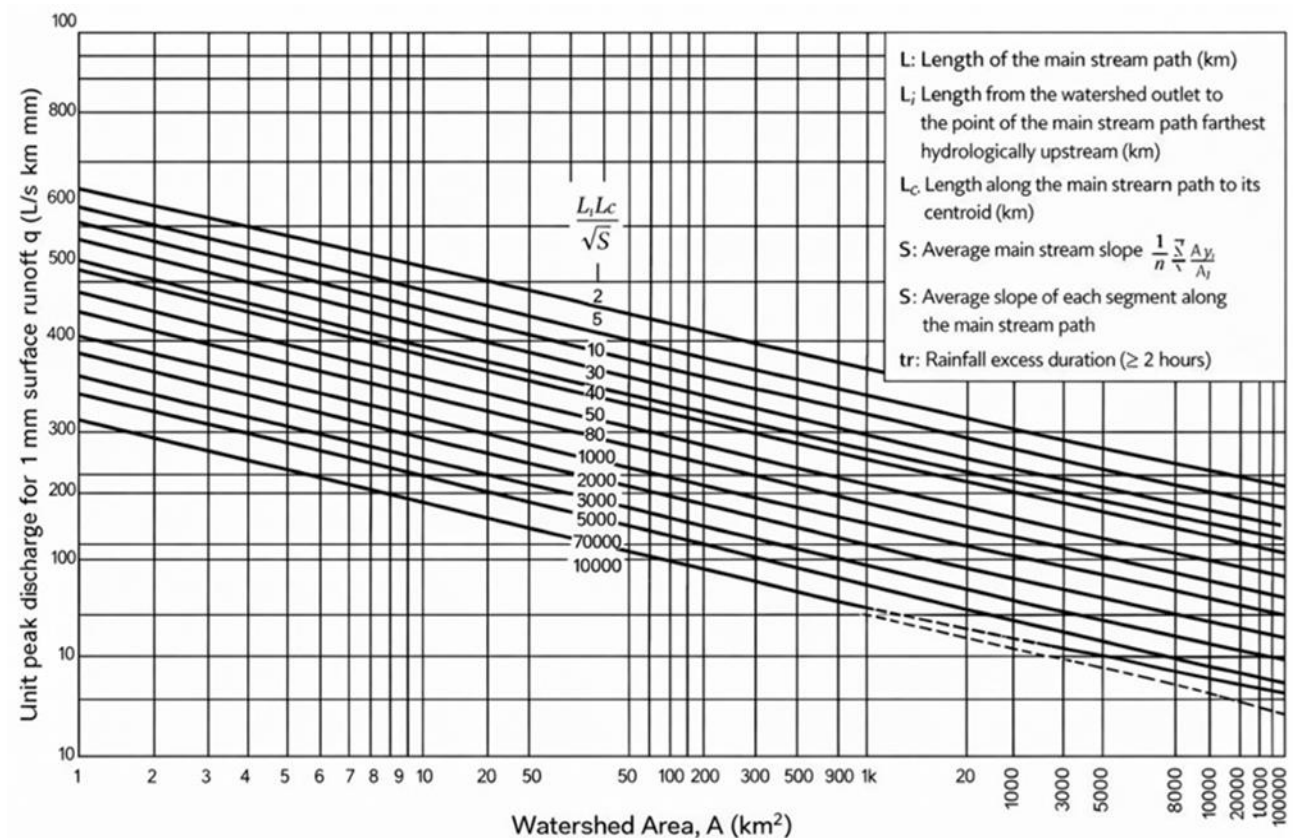
Appendix 1. Synthetic methods and empirical formulas

Mockus Method	DSİ Synthetic Method	Snyder Method
$T_c = 0,00032 \cdot (L^{0,77} / S^{0,385})$ (h) Equation (4)	$E = [L \cdot L_c] / \sqrt{S}$ Equation (8)	$t_p = 752 \cdot C_t \cdot (L \cdot L_c) T^{0,3}$ (h) Equation (12)
$D = 2\sqrt{T_c}$ (h) Equation (5)	$q_p = [414 / (A^{0,225} \cdot E^{0,16})]$ (lt/s/km ² /mm) Equation (9)	$T_r = t_p / 5,5$ (h) Equation (13)
$T_p = 0,5 \cdot D + 0,6 \cdot T_c$ (h) Equation (6)	$T_p = 20,78 / q_p$ (H) Formül (10)	$Q_p = 2760 \cdot C_p / t_p$ (lt/s/km ² /mm) Equation (14)
$Q_p = (K \cdot A \cdot ha) / T_p$ (m ³ /s/mm) Equation (7)	$Q_p = A \cdot q_p \cdot 10^{-3}$ (m ³ /s/mm) Equation (11)	$Q_p = A \cdot q_p \cdot 10^{0,4}$ (m ³ /s/mm) Equation (15)
$K = 0,208$ (Climate parameter for Türkiye)		$T_p = t_r / 2 + t_p$ (h) Equation (16)
		$C_p = 0,6$
		$C_t = 1,8$

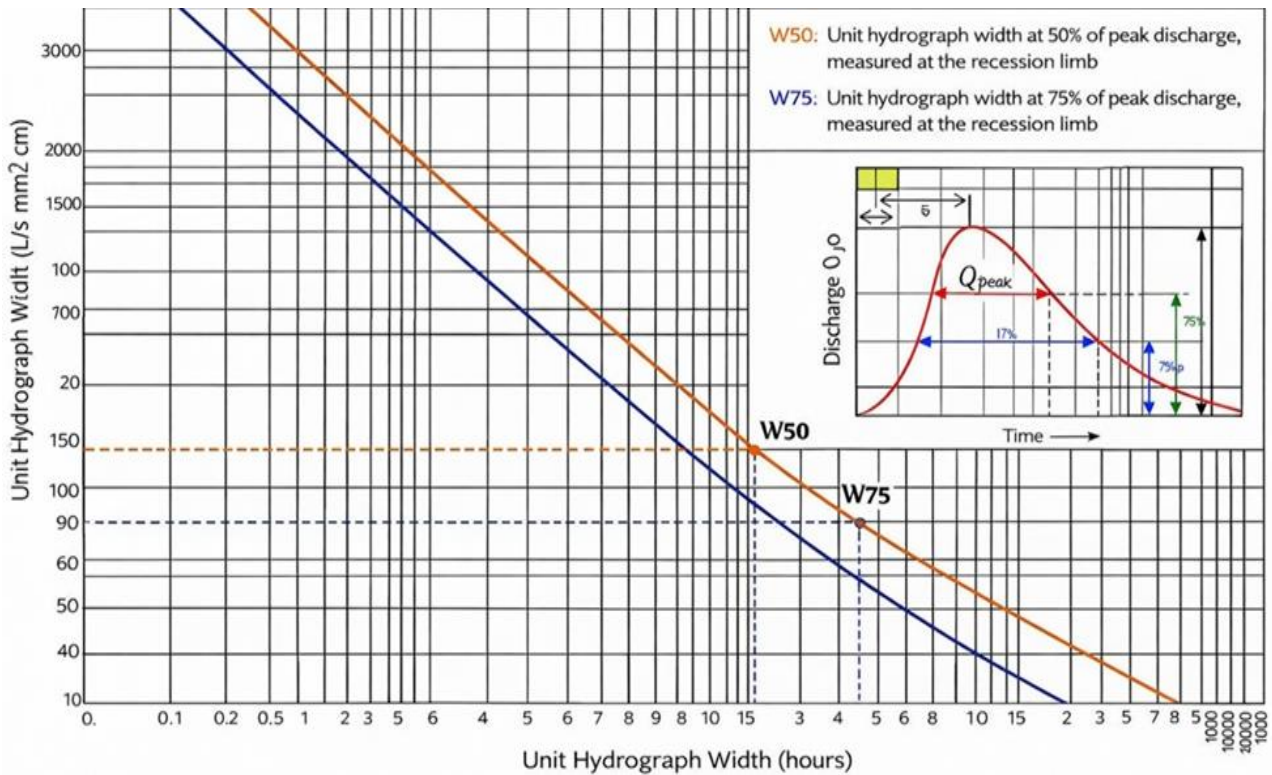
Appendix 2. Snyder method and ground-dependent Ct and Cp coefficients (Snyder, 1938; Özdemir, 1978; Singh, 1988)

Soil type	Ct	Cp
Sandy soil	1.65	0.56
Clay soil	1.50	0.63
Clayey or rocky soil	1.35	0.69

Appendix 3. Unit peak discharge (qp) diagram used in the DSİ Synthetic Unit Hydrograph method (DSİ, 2006)



Appendix 4. Diagram used to determine the W50 and W75 unit hydrograph widths in the Snyder Synthetic Unit Hydrograph method



Appendix 5. Components of the streamflow hydrograph

