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Original Research Article

Watershed Characteristics and Synthetic Unit Hydrographs Determination using Geographical Information Systems

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ABSTRACT

Precipitations and discharges are keys data in river watershed studies. In Nilüfer Dam Watershed, the flow values are measured every hour, whereas the cumulative rainfall values are recorded daily by the Public Water Management Department (DSİ). This study aimed to determine the characteristics of Nilüfer Dam Watershed and Synthetic Unit Hydrographs using Geographical Information Systems. The DSI synthetic method, Mockus method, and Snyder synthetic method were used in this study. For these three methods, the results showed a slightly significant difference between the discharge peaks of the resulting unit hydrographs. The highest discharge peak was achieved by the DSI Synthetic method (Qp = 4.40 m^3/sec/mm) and the smallest by the Mockus method (Qp = 3.75 m^3/sec/mm). The Mockus method achieved the longest basin lag time (Tp = 5.95 hours), and the shortest basin lag time was acquired by the Snyder method (Tp = 4.8 hours). This study suggests using synthetic methods for unit hydrographs determination in watersheds where there is no measured data.

Keywords: Geographical information systems, rainfall, synthetic unit hydrograph, watershed

INTRODUCTION

Water, an indispensable natural resource for life, is the key to socio-economic development and the protection of healthy ecosystems. With the population growth, the demands of agricultural and industrial sectors on underground and surface waters and their pressures on water resources are increasing. In recent years, efforts have been raised on integrated watershed management to ensure good water management. Within the scope of integrated watershed management, water supply, water quality control, quantitative water-related risk management, sediment control, biodiversity protection and recreational activities are discussed. Precisely estimating flood areas and flood-exposed areas in these regions is a matter of life to minimize flood damage. After heavy rains, especially prolonged heavy rains, flooding occurs particularly in over-sloped and impermeable soils. In order to take the necessary measures, long-term precipitation and current measurements should be made in the watersheds, and the watershed precipitation flow relationship should be determined. In some watersheds, not enough data are provided for evaluation. In this case, it is ensured that the assessment is made by using synthetic unit hydrograph methods.

The main aim of this study was to determine the watershed parameters using geographical information systems (GIS) techniques and synthetic unit hydrograph (UH) for the Bursa Nilüfer Dam Watershed. For this purpose, ArcGIS ArcMap (ESRI ArcGIS version 10.8, CA, USA) and Arc Hydro Tools were used primarily to determine the watershed boundary of the Nilüfer Dam. Furthermore, DSI synthetic method, Mockus method and Snyder method were applied. As unit hydrograph elements, parameters such as effective rainfall duration, basin lag time, peak discharge, and the base time of the unit hydrograph were determined. At the end of the study, the results obtained by these methods were evaluated and compared.

MATERIALS AND METHODS

Study area

This study was conducted in the Nilüfer Dam Watershed, located in the Nilüfer River Basin (40°00'43.82" N 29°06'59.57" E) in Turkey (Figure 1).

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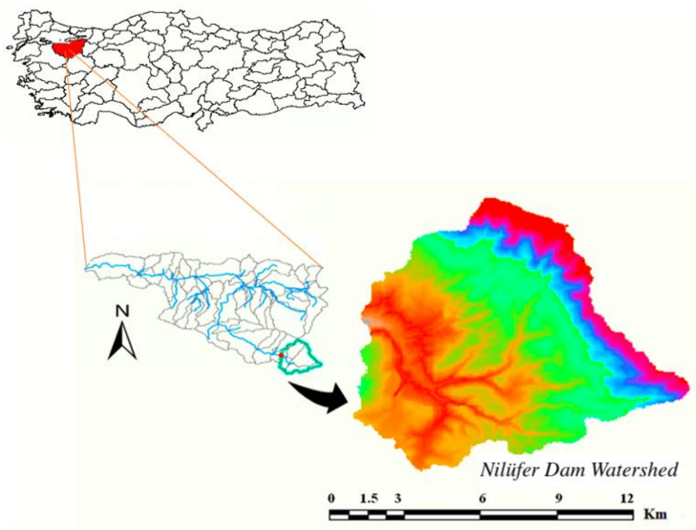

Figure 1. Location of Study Area.

The climate of the study area has the characteristics of the Marmara transition type of the Mediterranean climate. Although the region is close to the Marmara Sea, the mountain of Uludağ prevents the sea effect from being introduced. Precipitations are mostly seen in spring and winter. Winter precipitations are usually in the form of snow. The land use and land cover of the Nilüfer Dam watershed are variable: 39.25% of the land is fallow land, 34.48% is forest, and 15.19% is shrubbery land. 4.43% is classified as garden watery, 4.25% pasture, 0.56% aqueous agriculture and 1.85% others (Bantchina *et al.* 2017).

Numerical and non-numerical data were used within the scope of the study. Meteorological data were obtained from the Turkish General Directorate of Meteorology. ASTER DEM data of 30x30 m resolution were downloaded from the USGS website and used for watershed delineations and topographic parameterization.

Methodology

In this study, ArcGIS ArcMap (ESRI ArcGIS version 10.8, CA, USA) software and Arc Hydro Tools were used to determine the watershed parameters (Anonymous, 2021). DSI synthetic, Mockus, and Snyder methods were used as synthetic UH methods. The flow chart of the methodology followed in this study is given in Figure 2.

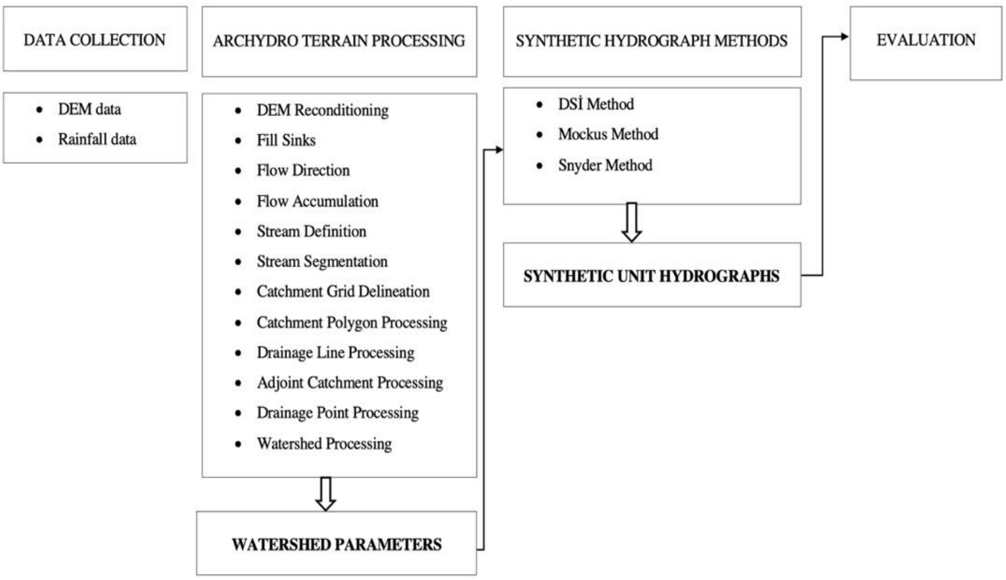

Figure 2. Flow chart of the methodology followed in this study.

DSI Synthetic Method

In the DSI synthetic method, UH values are calculated using the watershed efficiency generated by two hours of rainfall that produces 1 mm flow in stream basins with a precipitation area of up to 1000 km^2. The following formulas below were used to calculate unit hydrograph elements by using the DSI synthetic method (Özdemir 1978).

$$S = \left(\frac{10}{\sum \frac{1}{\sqrt{Si}}} \right)^2 \quad (1)$$

$$E = \frac{L.Lc}{\sqrt{S}} \quad (2)$$

$$Q_p = A.q_v.10^{-3} \quad (3)$$

$$T = 3.65\left(\frac{V_b}{Q_p}\right) \quad (4)$$

$$T_p = \frac{T}{5} \quad (5)$$

$$V_b = A.ha.10^3 \quad (6)$$

Where: Qp is the peak discharge (m^3/sec/mm); T is the hydrograph continuation time (sec); Tp is the basin lag time (hours); Vb is the unit volume (m^3); S is the harmonic slope of the mainstream; ha is 1 mm flow height; A is the basin area (km^2); L is the length of the mainstream (m); Lc is the distance from the outlet to a point on the stream nearest the measure of watershed shape.

Mockus Method

The Mockus method can be used in basins with up to 30 hours of concentration time. The larger basin is divided into sub-basins in basins with a more significant collection time. Hydrographs for the larger basin can be obtained using the hydrographs created for each sub-basin. The Mockus method is preferred since it is easy to process and work on the drawn triangular hydrograph.

Due to the precipitation variability, it is essential to select the ΔD unit downpour time to be taken in the floods to be calculated. In the selection of ΔD unit downpour time, the criteria are usually Tc/5 ≤ ΔD. For the first 6 hours of project downpour time, ΔD is mostly 1 hour. If the Tc is less than 3 hours, it is practically taken 1/2 hour. If the Tc is between 10 and 15 hours, ΔD = 2 hours, and from 15 hours to 30 hours, it is recommended to take ΔD for 3 hours. The following formulas are used when determining synthetic UH by using the Mockus method (Özdemir 1978).

$$T_c = 0.00032\frac{L^{0.77}}{S^{0.385}} \quad (7)$$

$$D = 2\sqrt{Tc} \quad (8)$$

$$T_p = \sqrt{Tc} + 0.6\,Tc \quad (9)$$

$$T_r = H.T_p \quad (10)$$

$$T_b = T_p + T_r \quad (11)$$

$$Q_p = \frac{K.A.ha}{T_p} \quad (12)$$

$$K = \frac{Q_p.T_p}{A} \quad (13)$$

$$H = \frac{(2 \times 0.278 - K)}{K} \quad (14)$$

Where: Tc is the concentration time (hours); Qp is the peak discharge (m^3/sec/mm); Tp is the basin lag time (hours); Tr is the effective rainfall duration (hours); Tb is the base time (hours); ha is the annual average unit precipitation (mm); D unit downpour time (hours); A is the basin area (km^2); L is the length of the mainstream (m); S refers to the harmonic slope of the mainstream. K and H are the coefficients based on basin characteristics.

Snyder Method

The synthetic UH of Snyder (1938) is based on relationships between three characteristics of a standard unit hydrograph and descriptors of basin morphology. The Snyder method can be applied to drainage areas up to 25-25000 km^2, and in larger areas, calculations are made by dividing them into secondary basins. Snyder used three parameters (the effective rainfall duration (Tr), the peak direct runoff rate (Qp), and the basin lag time (Tp)) to describe the unit hydrograph. Snyder found the following relationship between Tr and Tp for a standard unit hydrograph.

$$T_r = \frac{T_p}{5.5} \quad (15)$$

For a standard unit hydrograph, the basin lag Tp, and the peak discharge Qp, are given by:

$$T_p = Ct(L.Lc)^{0.30} \quad (16)$$

$$Q_p = A.qv.ha.10^{-3} \quad (17)$$

Where L is the length of the mainstream (m), Lc is the distance from the outlet to a point on the stream nearest the measure of watershed shape (m), and Ct is a coefficient derived from gauged watersheds in the same region.

$$qv = 276\frac{C_p}{T_p} \quad (18)$$

Where: qv is the flow efficiency (lt/sec/km²/mm); Cp is a coefficient derived from gauged watersheds in the area and represents the effects of retention and storage.

The hydrograph time T (days) is:

$$T = 3 + \frac{3.T_p}{24} \quad (19)$$

RESULTS AND DISCUSSION

Determination of Nilüfer Dam Watershed Parameters

Nilüfer Dam Watershed characteristics were determined using a digital elevation model of the study area. The results are given below in Figure 3.

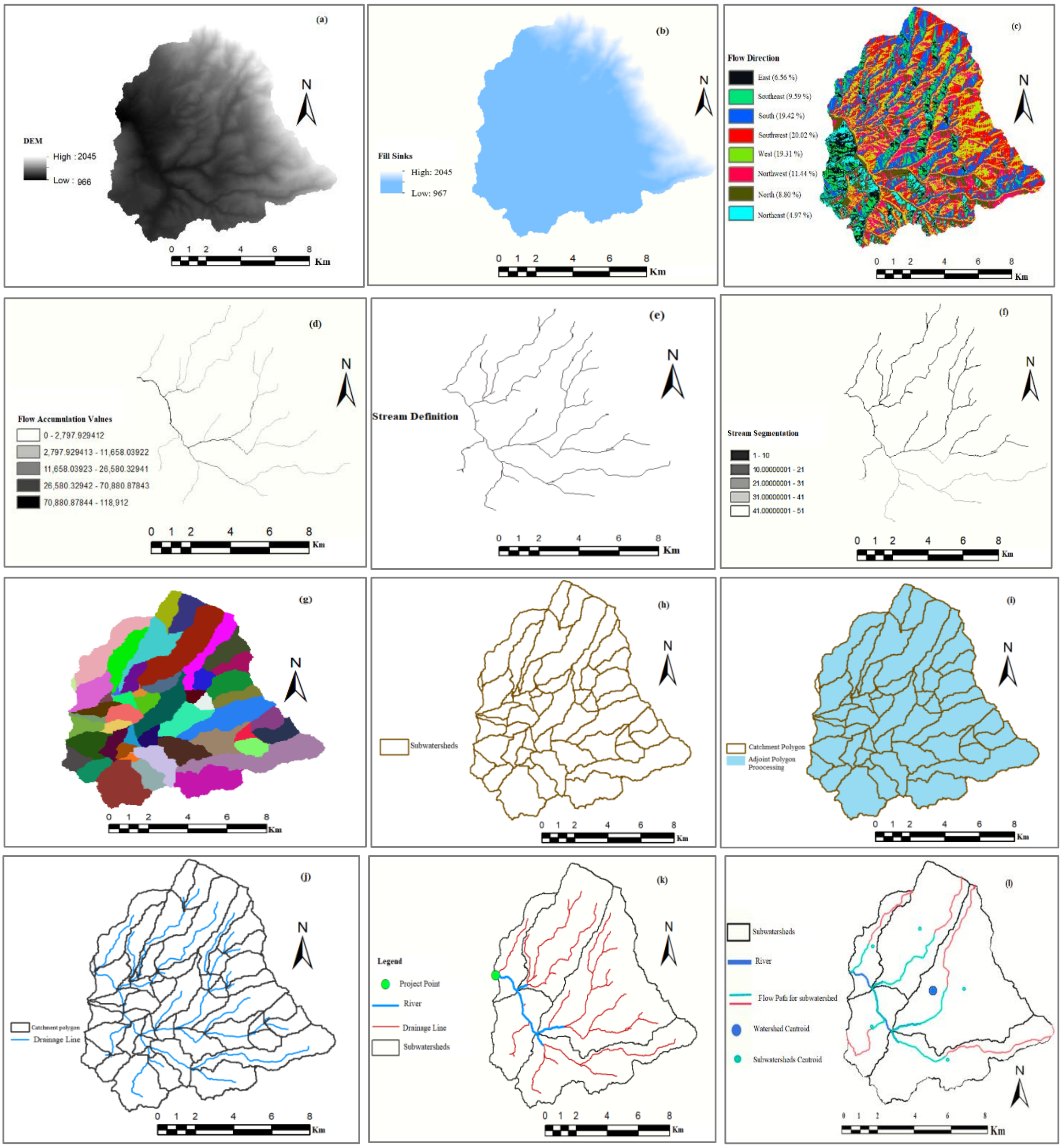

Figure 3. (a) DEM, (b) Fill Sinks, (c) Flow Direction, (d) Flow Accumulation, (e) Stream Definition, (f) Stream Segmentation, (g) Catchment Grid Delineation, (h) Catchment Polygon Processing, (i) Drainage Line Processing, (j) Adjoint Catchment Processing, (k) Drainage Point Processing, (l) Watershed Processing.

The numerical data obtained from Nilüfer Dam Watershed are given below in Table 1.

Table 1. Numerical values of Nilüfer Dam Watershed

Watershed Characteristics	Results
Watershed Area (km^2)	A = 107.35
Watershed Perimeter (m)	13101.3
Watershed minimum height (m)	966
Watershed maximum height (m)	2045
Watershed mean height (m)	1362.07
Watershed Direction	Southwest, South
Watershed Longest Flow Path (m)	L = 17875.9
Centroidal Longest Flow Path (m)	Lc = 6964.66

Determination of Unit Hydrograph by using DSI Synthetic Method

The UH of the Nilüfer Dam Watershed obtained by the DSI synthetic method is a hydrograph for a period of 2 hours. The peak discharge was Qp = 4.40 m^3/sec/mm, and the basin lag time was Tp = 5 hours (Figure 4).

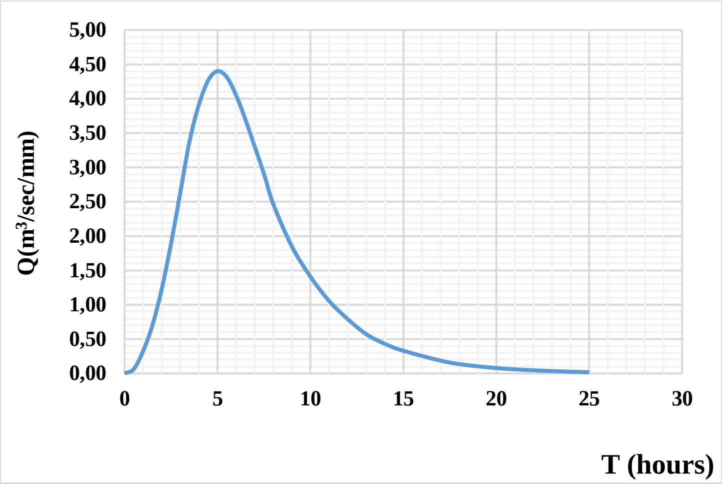

Figure 4. UH obtained by using DSI synthetic method for Nilüfer Dam Watershed.

Determination of Unit Hydrograph by using Mockus Method

According to the Mockus method, the UH peak discharge is Qp = 3.75 m^3/sec/mm, the base time Tb is 15.89 hours, the basin lag time is Tp = 5.95 hours, and the effective rainfall duration Tr is 9.94 hours. According to the Nilüfer Dam Watershed characteristics used in this method, the coefficients were found to be K = 0.347 and H = 0.602 (Figure 5).

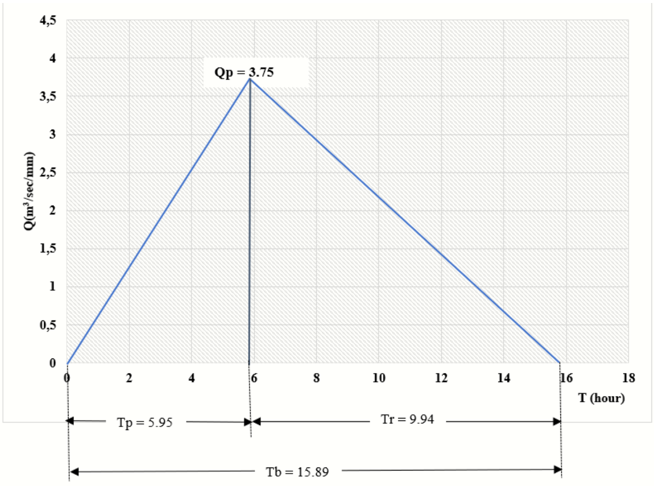

Figure 5. UH obtained by using the Mockus method for Nilüfer Dam Watershed.

Determination of Unit Hydrography by using the Snyder Method

With the Snyder method, for the Nilüfer Dam Watershed, UH elements obtained are the peak discharge Qp = 3.89 m^3/sec/mm, the effective rainfall duration Tr = 1 hour, the basin lag time Tp = 4.8 hours; and the coefficients according to the basin and unit hydrograph characteristics are Ct = 1.5; Cp = 0.63 (Figure 6).

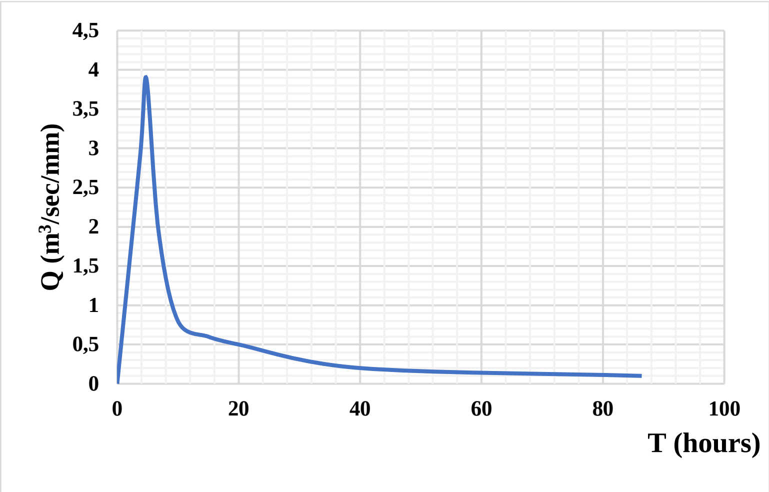

Figure 6. Snyder's Synthetic UH for Nilüfer Dam Watershed.

Using the DSI synthetic method, the UH of the Nilüfer Dam Watershed obtained is a hydrograph for 2 hours. The peak discharge was Qp = 4.40 m^3/sec/mm, and the basin lag time was Tp = 5 hours. With the Mockus method, the UH peak discharge is Qp = 3.75 m^3/sec/mm, the base time Tb is 15.89 hours, the basin lag time is Tp = 5.95 hours, and the effective rainfall duration Tr is 9.94 hours. According to the Nilüfer Dam Watershed characteristics used in this method, the coefficients were found to be K = 0.347 and H = 0.602. By using the Snyder method, the UH elements obtained are the peak discharge Qp = 3.89 m^3/sec/mm, the effective rainfall duration Tr = 1 hour, the basin lag time Tp = 4.8 hours; and the coefficients according to the basin and unit hydrograph characteristics are Ct = 1.5; Cp = 0.63.

For these three methods, the results showed a slight difference between the discharge peaks of the resulting unit hydrographs. The highest discharge peak was achieved by the DSI Synthetic method (Qp = 4.40 m3/sec/mm) and the smallest by the Mockus method (Qp = 3.75 m3/sec/mm). The Mockus method achieved the longest basin lag time (Tp = 5.95 hours), and the shortest time was achieved by the Snyder method (Tp = 4.8 hours).

These results are consistent with the results obtained by Sönmez et al. (2012). In the Snyder method, the Ct and Cp coefficients are connected to the ground, and in the Mockus method, K and H coefficients are the coefficients related to the basin properties. In order to find these coefficients, preliminary studies are required. The DSI method does not require these coefficients; therefore, this method should be preferred.

Göçmen (2006) compared the results of empirical methods such as SCS dimensionless, Snyder, Mockus, Turc, Mc Math and Rational with field measurements. He concluded that Snyder and Mockus methods gave better results for basin flood flow and hydrographs.

In his study, Alkan (2016) calculated and compared the flood flow rate in some pond basins of Bursa Province by applying Mockus, Rational and DSİ synthetic methods and the WinTR-55 model.

In the study of İstanbulluoğlu et al. (1997) aimed to determine the precipitation and flow relationships in the Bursa-İznik Mahmudiye watershed, which is located in the north of Iznik. To characterize the precipitation amount in the basin, daily corrected total maximum precipitation depths were obtained from the Mecidiye and Boyalıca meteorological stations. As a result, they found a polynomial relationship between precipitation and runoff.

In the study conducted by Yılmaz et al (2015), it was aimed to obtain instantaneous unit hydrographs for the Tokat-Akdoğan stream basin. Geographic Information Systems (GIS) software, which is widely used, was used to obtain instant unit hydrographs. With the help of ArcGIS program, some basin characteristics were determined by using the 30-meter resolution ASTER GDEM digital elevation model data of the study area. The instantaneous unit hydrographs were obtained by the Rodriguez-Iturbe and Valdes methods, as well as the Gupta and Waymire methods. They concluded that the instantaneous unit hydrographs obtained with the help of GIS can be easily used for the estimation of flood flows in river basins that do not have reliable measurements.

Günel and Güven (2016) compared the values measured in 3 different basins with the results obtained in synthetic hydrographs and found the following results: Peak discharge, Qp values in Snyder method are underestimated for all catchments. Base time, Tb values in Snyder method are overestimated for all catchments. Peak discharge, Qp values in Mockus method are underestimated for Vize and Kumdere catchment and overestimated for Damlıca catchment because of the shape factor of these catchments. Base time, Tb values in Mockus method are underestimated for all catchments. Peak discharge, Qp values in SCS method are reasonably well predicted in Damlıca catchment when using both the topographic map and the GIS values but overestimated for Kumdere and Vize catchments. Base time, Tb values in SCS method are underestimated for all catchments. Peak discharge, Qp values in DSI method are underestimated in Vize and Kumdere catchments but overestimated in Damlıca catchment because of the shape factor. Base time Tb values in DSI method are underestimated for all catchments.

CONCLUSIONS

Nilüfer Dam Watershed parameters were obtained by using GIS techniques. Nilüfer Dam is a watershed with an area of 107.35 km^2. The watershed circumference length is 62520 m, the maximum height value is 2045 m, and the minimum height value is 966 m. The length of the mainstream of the watershed is 17875.9 m; the distance from the outlet to a point on the stream nearest the measure of watershed shape is 6964.66 m.
Synthetic UH were created with these obtained watershed characteristics. DSI Synthetic, Mockus and Snyder's methods calculated the discharge peak (Qp), the basin lag time (Tp), the base time (Tb) of the average unit hydrograph with a duration of 2 hours, and some coefficients of these methods were obtained.

The results showed that Synthetic unit hydrograph methods can be used in the preparation of hydrographs related to similar watersheds. However, differences can occur according to the results obtained using actual current observation and climate values related to the watershed. However, synthetic methods may be mandatory in UH determination in watersheds where there is no measured data.

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