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Analysis of Monthly Precipitation at the Basin Scale in Türkiye

Hasan Hüseyin Aksu[1,a,*]

[1]*Department of Architecture and Urban Planning, GIS Division, Bucak Emin Gülmez Vocational School of Technical Sciences, Burdur Mehmet Akif Ersoy University, Burdur, Türkiye.*
[*]*Corresponding author*

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ABSTRACT

Basin-based water management strategy is one of the necessary instruments for the protection and sustainable use of water resources against climate change. In this paper, the monthly precipitation distributions of the 25 major basins in Türkiye were produced, and amounts and volumes were computed and analyzed. Only annual modeling and assessments of precipitation may hide months with precipitation shortages. Empirical Bayesian Kriging (EBK), Ordinary Kriging (OK), and Inverse Distance Weighting (IDW) were implemented in interpolation. EBK outperformed in all months and calculations were based on the EBK. The month with the highest precipitation potential in Türkiye is December (77.9 mm, 60.77 billion m^3), and the month with the lowest precipitation potential is August (13.8 mm, 10.76 billion m^3). In the basins, the monthly precipitation amounts range between 2.7 mm and 185.2 mm, and the volumes range between 0.02 billion m^3 and 13.24 billion m^3. The basins with the highest precipitation depth were determined as the East Black Sea, Antalya, Asi, and Ceyhan, and the lowest as the Small Menderes, Konya, and Tigris-Euphrates in different months. The monthly precipitation patterns and potentials of the basins vary widely. In May, June, July, August, and September, when water, particularly agricultural irrigation, is required the most, the 20 basins, except for the 5 located in Northern Türkiye precipitation shortage was determined.

[a] *haksu@mehmetakif.edu.tr* *https://orcid.org/0000-0003-3649-7242*

Introduction

Precipitation is the major source of freshwater and is the key input for calculating the water potential and water policies of a watershed or a country. In many studies, particularly on sustainable use of water resources, agricultural irrigation, floods, drought and watershed management, and climate change, determining the precipitation model as close to reality as possible is crucial. Accurate rainfall information is vital for decision-makers. Rainfall is an intermittent climatic element, with major temporal and spatial instability and discontinuity. Therefore, a more frequent measurement network than the other meteorological parameters is required for precipitation. Precipitation data can be obtained from meteorological satellites and radars as well as rain gauges (Akgül and Aksu, 2021). Rain gauge-based rainfall measurements are the best for their accuracy. The precipitation measurement is performed at a certain place and represents that specific location. It is not possible to set up stations at any desired location because of financial and geographical limitations. Spatial precipitation data obtained from point precipitation data via interpolation methods are used in hydrological practice (Goovaerts, 1997; Ly et al., 2013)

There are two requirements for modeling an accurate precipitation distribution map and calculating the potential: First, an optimum raingauge network, which can best represent the study area; second, the optimum interpolation method. The use of non-homogeneous, inadequate, and off-target precipitation data causes numerous difficulties. The accuracy of rainfall estimation increases as the number of raingauges increases; however, fewer raingauges eventually decrease the accuracy of areal precipitation estimations and increase estimation errors (Berne et al., 2004; Cheng et al., 2012; Shehu and Haberlandt, 2021). In this respect, the World Meteorological Organization (WMO) suggests that the observation data should cover at least 30 years, and in regions such as Türkiye, there should be at least one raingauge every 2500 km^2 (WMO, 2008). As per this suggestion, there should be at least 312 raingauges in Türkiye, which has 780,000 km^2 of surface area.

It was reported in many studies conducted using precipitation data in Türkiye that the frequency and homogeneity of precipitation stations were not at the desired level (Kadioglu et al., 1999; Çıtoğlu et al., 2017; Raja et al., 2017; Aksu, 2020; Aksu, 2021).

Turkish State Meteorological Service (TSMS) is the foundation that observes all climate elements and provides data for studies in this field. TSMS has 254 stations of usable quality. These stations are centered around inhabited areas and are not homogeneously distributed over the country. Since the early 2000s, Automated Weather Observing System (AWOS) has been set up at more than 2000 locations, and precipitation observations have been recorded. These stations cannot yet be used in studies because of inadequate data periods (at least 30 years). On the other hand, Turkish State Hydraulic Works (TSHW), which is the foundation in charge of hydraulic works in Türkiye, operates water-shed-based precipitation and evaporation observations around dams and ponds. TSHW has 137 precipitation stations of usable quality. The rural TSHW stations and the urban TSMS stations complement each other. In this study, TSHW stations were used in addition to TSMS stations.

Spatial interpolations are mathematical equations or methods, which estimate data in unmeasured areas by using the data of measured areas. There are various interpolation methods. Implementation of a suitable interpolation method varies from region to region. The selection of the method depends on factors, such as the aim of the study, the density of stations, and the topography of the area. The density of the station network affects the performance of interpolation. In areas, where the observation network is dense, interpolation methods show similar spatial distribution (Borges et al., 2016; Frazier et al., 2016)

There are many studies in the literature, in which deterministic and geostatistical methods for precipitation data interpolation are used in various areas. Studies are centered around comparisons of methods to find the most suitable method (Sun et al., 2015; Borges et al., 2016; Antal et al., 2021; Das, 2021).

There are papers in Türkiye, in which deterministic and geostatistical techniques were used or compared for the interpolation of rainfall data (Türkoğlu et al., 2016; Çıtoğlu et al., 2017; Raja et al., 2017; Aksu, 2021; Aksu, 2023)

Monthly rainfall data provide more correct intra-yearly rainfall knowledge than annual and seasonal rainfall data. Only annual assessments of precipitation distribution may hide months of the year with precipitation shortages. Monthly rainfall information is an element that makes significant additions to the monitoring of drought and climate change, basin and water resources management, and agricultural and hydrological practices. Although there are many studies investigating the annual and seasonal potential and variability of precipitation in Türkiye (Kadıoğlu et al., 1999; Türkeş et al., 2009; Çiçek and Duman 2015; Raja et al., 2017; Türkeş, 2020a; Aksu, 2021, Aksu, 2023). There is no study in the literature explaining the watershed-based monthly potential and spatial distribution of precipitation.

This study aims to determine and analyze the monthly precipitation potentials and models of the 25 major basins in Türkiye. Therefore, geostatistical EBK and OK, and deterministic IDW techniques were implemented in the GIS environment. Results were compared through the cross-validation method. In the work, different from the earlier research in Türkiye, monthly precipitation data from two foundations (TSMS and TSHW) were joined to fulfill the rain gauge network intensity recommendation of the WMO. The location and intensity of the rain gauge network influence the accuracy of precipitation estimation (Borges et al., 2016; Frazier et al., 2016)

With its semi-arid precipitation regime, and 1500 m^3 of yearly water amount per individual, Türkiye is among the water-scarce countries (Falkenmark 2013; Aydın et al., 2017; Türkeş, 2020a). Water consumption in Türkiye has increased by approximately 40% within the last 20 years (Aksu, 2021). More than 70% of the water supply is used for irrigation purposes in Türkiye (MAF, 2019). Basin-scale water administration is one of the necessary instruments for the protection and sustainable use of water resources against drought that may happen depending on climate change and ever-growing water demand (WFD, 2000). This paper is crucial for watershed administration since Türkiye has been working on an integrated watershed-scale water administration model for adaptation to climate change. At the same time, this study is also important in monitoring monthly precipitation changes at the basin scale depending on climate change as Türkiye is situated within the Mediterranean and Middle East regions, which are largely affected by climate change (WWDR, 2020; Türkeş, 2020b; WWDR, 2021).

Materials and Methods

Study Area and Data

Türkiye is situated in the Mediterranean basin between 26-45^0 eastern meridians and 36-42^0 northern latitudes and is surrounded on three sides by the sea (Figure 1). Marina climate and precipitation can penetrate the inner basins of the country by weakening since The Taurus Mountains at the south and the Black Sea Mountains at the north lay parallel to the seaside. Because of the large number of tectonic graben horst systems extending in an east-west direction in Western Türkiye, rainfall can penetrate the interior parts of this area. The hills facing the Black Sea in the North and the Mediterranean Sea in the South are the zones of the country with the most precipitation. Altitude in Türkiye goes up to 5137 meters above sea level, and the average altitude is around 1100-1200 meters. The average altitude gradually increases from west to east. Because of the unstable topography of the country, major precipitation differences may be observed over short distances.

Türkiye has 25 major watersheds. The watersheds covering the greatest area are Tigris-Euphrates (175,882 km^2), followed by Kızılırmak (82,082.5 km^2), Sakarya (63,242.9 km^2), and Konya (49,805.3 km^2) watersheds, respectively. There are twelve watersheds covering between 20,000 and 30,000 km^2 of area. Burdur (6,273.8 km^2), Small Menderes (7,027.1 km^2), Asi (7,904.2 km^2), Akarçay (7,954.5 km^2), and North Aegean (9,963.6 km^2) are watersheds covering smaller areas.

While 17 watersheds are located by the sea, 8 watersheds are landlocked areas. The landlocked watersheds are Akarçay, Burdur, and Konya in Central Anatolia, Tigris-Euphrates, Van, Aras, and Çoruh in Eastern Anatolia, and Meriç-Ergene in Northwest Anatolia. Tigris-Euphrates, Asi, Çoruh, Aras, and Meriç-Ergene are transboundary watersheds. Tigris-Euphrates, Aras, and Çoruh are upstream watersheds; Asi and Meriç-Ergene are downstream watersheds.

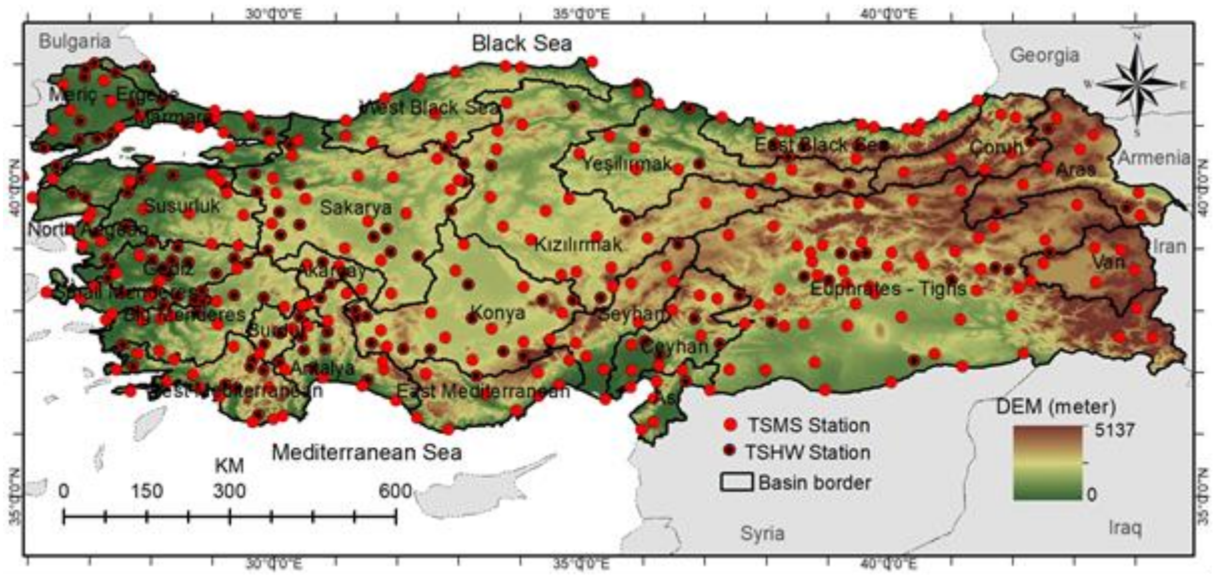

Figure 1. Rain gauge station network and watersheds on an elevation model of Türkiye

The annual precipitation amount of Türkiye is 587 mm and this value varies between 1013 mm (East Black Sea) and 389 mm (Konya) in the watersheds (Aksu, 2021). Antalya (939 mm), West Mediterranean (834), and Asi (800 mm) are the wettest watersheds of Türkiye after the East Black Sea watershed. In the 7 watersheds, the annual rainfall amount is below 500 mm.

In the study, the monthly precipitation data of 391 raingauges (254 of which are operated by TSMS and 137 by TSHW) for the period between 1965 and 2018 were used. Figure 1 shows the watersheds in Türkiye and the locations of TSHW and TSMS raingauges.

Methodology

The interpolation technique is a method used for estimating values at unmeasured locations by using the data of points, where measurements of variables were conducted. Variables in neighboring locations give more similar results than remotely located variables. The geostatistical EBK and OK, and deterministic IDW techniques were used in the study for areal interpolation of monthly precipitation data. Geostatistical analyst tools of the Geographic Information Systems (GIS) program ArcGIS 10.8 were used for the implementation of interpolation methods and to create an areal distribution map of monthly precipitation data. *Ordinary Kriging (OK)*

OK is the most widely used Kriging technic (Goovaerts, 1997; Ly et al., 2013). In the OK method, first, an experimental semi-variogram analysis of the observation data is performed. Then theoretic semi-variogram model is adapted (fitted) to this structure. The theoretic semi-variogram is obtained by applying an algebraic function to the experimental semi-variogram. Spherical, circular, and Gaussian variogram models are widely used in precipitation data. Gaussian and circular models were the most suitable theoretic models for this study. The formulas of the experimental semivariance, the Gaussian, and the Circular theoretical models are shown respectively below (Webster and Oliver, 2017):

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(X_{m_i}) - Z(X_{m_i} + h)]^2 \qquad (1)$$

$$\gamma(h) = C_0 + C_1 \left[1 - \exp\left(\frac{-3h^2}{a^2}\right)\right] h \geq 0 \qquad (2)$$

$$\gamma(h) = \begin{cases} C_0 + C_1 \left[1 - \frac{2}{\pi} cos^{-1}\left(\frac{h}{a}\right) + \frac{2h}{\pi a}\sqrt{1 - \frac{h^2}{a^2}}\right] h \leq a \\ C_0 + C_1\ h > a \end{cases} \qquad (3)$$

$\gamma(h)$: function of semi-variogram, hinge on lag or h interval; h: interval vector; $Z(X_{me,i})$: measured rainfall of every i location; $Z(X_{me,i} + h)$: measured rainfall interval h from i location; $N(h)$: data pairs number; C_1: partial sill; C_0: nugget effect; a: range. Kriging, which is the fundamental instrument of geostatistics, is the best linear unbiased estimator. Its ability to calculate the variance value for each estimated point is the defining characteristic of this technique. Estimation is performed with the weighted average of the measured value. The weightings are based on the distance and the model variogram. The basic formula used in OK is given as equation (4) (Webster and Oliver, 2017).

$$\hat{Z}_{OK}(X_0) = \sum_{i=1}^{N} W_i^{OK} Z(X_{me,i}) \qquad (4)$$

$\hat{Z}_{OK}(X_0)$: estimated OK rainfall value at X_0 location; W_i^{OK}: weight for each $Z(X_{me,i})$ location; $X_{me,i}$: measuring point; N, shows the number of locations used in OK estimation. After the theoretical semivariogram structure of the investigated variable (precipitation) is determined mathematically (equations 2, 3), the values of the unobserved points in the study area are estimated with the OK (equation 4) technique.

Empirical Bayesian Kriging (EBK)

Geostatistical EBK is a reliable and simple way for automatic interpolations of variables (Li et al., 2022). EBK does not require its users to manually regulate parameters to get accurate outcomes (Gribov and Krivoruchko, 2020). Classical Kriging methods compute the semi-variogram from observed data points and utilize this single calculated semi-variogram to make predictions at unknown points. After this process, the predicted semi-variogram is assumed to be the true semi-variogram for the interpolation area. Unlike classical Kriging methods, EBK uses many semi-variogram models and takes account of the errors that happen when estimating the semi-variogram models. Therefore, this process of EBK causes standard estimation errors to be more accurate than traditional Kriging techniques (Zou et al., 2021). EBK semi-variogram prediction process requires the steps below (Krivoruchko, 2012):

1. A semi-variogram model is estimated from the measured data.
2. Using the estimated semi-variogram model, new data at each input point is simulated.
3. A new semi-variogram model is predicted using the simulated data. Using Bayes' rule, the weights of the new semi-variogram are computed. Bayes' rule measures the likelihood of a predicted semi-variogram to simulate observed data.

Inverse distance weighted (IDW)

The IDW is frequently used in the spatial interpolations of many variables, especially climate parameters. The weight of precipitation values measured at a short distance has a greater influence on the predicted rainfall values than those measured at long distances (Borges et al., 2016). The general equation of IDW is as follows:

$$R_{p_j} = \frac{\sum_{j=1}^{N} \frac{1}{d_i^P} R_{O_j}}{\sum_{j=1}^{N} \frac{1}{d_i^P}} \tag{5}$$

N is the number of rainfall observation locations used for the prediction. R_{p_j} is the rainfall to be predicted. R_{O_j} are the observed rainfall values. d_i are distances between R_{p_j} and R_{O_j} points. P is the power parameter. Weightage degrees of observed values are controlled by exponent power. The weight of the precipitation values of the close neighbors in the interpolation increases as the power value increases.

Cross-validation

Cross-validation is a method, which is frequently used for the evaluation and comparison of spatial interpolations. By the method, the relations between measured and estimated values are examined. For this purpose, the rainfall value of one station is temporarily separated from the data set. The rainfall value of the separated point is estimated by utilizing the rainfall data of the remaining raingauges. This application is implemented in each rainfall station. The error margin between the measured and estimated precipitation value is measured. Various error measurement methods are used in the evaluation of produced data (Frazier et al., 2016; Antal et al., 2021). In this study, Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and Determination Coefficient (R^2) were used. MAE and RMSE measures are widely applied because of their theoretical relevance in statistical modeling (Bagirov et al., 2017). RMSE shows the size of the error. Since the weight of major errors is greater, they are sensitive to extreme values. MAE gives a mean error estimate, and it is not affected by extreme values. Low MAE and RMSE values show verisimilitude of the estimated precipitation values. R^2 represents the relationship between observation and estimated values. It indicates the power of the linear relation. The formulas for these techniques are presented below:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|V_{m_i} - V_{e_i}\right| \tag{6}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(V_{m_i} - V_{e_i})^2} \tag{7}$$

$$R^2 = \left\{\frac{\sum_{i=1}^{n}\left(V_{m_i}-\bar{V}_m\right)\left(V_{e_i}-\bar{V}_e\right)}{\left[\sum_{i=1}^{n}\left(V_{m_i}-\bar{V}_m\right)^2\right]^{1/2}\left[\sum_{i=1}^{n}\left(V_{e_i}-\bar{V}_e\right)^2\right]^{1/2}}\right\} \tag{8}$$

V_m: measured rainfall value; V_e: estimated rainfall value; $\bar{V}_m$: average of measured rainfall values.

Results

The addition of 137 TSHW raingauges to 254 TSMS raingauges has increased the number of available raingauges by 54%. The area represented by 1 raingauge has been increased from 3071 km^2 to 1995 km^2. Therefore, WMO's standard of at least one raingauge in every 2500 km^2 in topographies like Türkiye has been achieved.

Table 1 indicates the statistical results of the monthly rainfall data of 391 observation points in Türkiye. The maximum precipitation was found to be 324.4 mm in December, and the minimum was 0 mm in July and August. The mean monthly precipitation values of these stations range between 16.1 mm in August and 92.9 mm in December. When evaluated together with other statistical data, it was found that precipitation in Türkiye showed great differences within and between months.

The monthly average precipitation histograms of the stations are demonstrated in Figure 2. The monthly mean rainfall is below 16 mm at 269 stations in July, 19 mm at 307 stations in August, and 29 mm at 304 stations in September. On the other hand, the average precipitation is over 300 mm at 1 station in January, and at 2 stations in October and December. The stations with lower precipitation levels have higher frequencies; the stations with higher precipitation levels have lower frequencies.

In order to determine the optimum model for each interpolation method, various parameters, such as power coefficient, neighborhood, sector, transformation, and semi-variogram, were tested until a minimum error rate was obtained. In the IDW method, the optimum power coefficient ranged between 2.04 and 3.93 (Table 2). Figure 3 shows the experimental and theoretical models and parameters, which ensure optimum monthly results for the OK method. In the EBK method, empirical and log empirical were used as transform types, and whittle-detrended and K-Bessel detrended were used as a semi-variogram model (Table 3).

When the monthly precipitation distribution models derived were analyzed, it was found that the OK (Figure 4), EBK (Figure 5), and IDW (Figure 6) methods created similar patterns. As expected, the bull's eye effect was observed around the measuring points on the maps attained through IDW. The distribution maps obtained through OK and EBK formed a precipitation pattern in concordance with the topography.

The errors and performance results revealed through cross-verification applied to compare OK, EBK, and IDW techniques, are presented in Table 2. In IDW, R^2 was found between 0.52 (April) and 0.85 (August), RMSE was found between 8.15 (July) and 31.22 (December); MAE was found between 4.24 and 21.9. In OK, R^2 was found between 0.56 (April) and 0.87 (July and August), RMSE was found between 7.4 (July) and 29.06 (December); MAE was found between 3.8 and 20.42. In EBK, R^2 was found between 0.64 (April) and 0.92 (August), RMSE was found between 6.43 (July) and 26.03 (December); MAE was found between 3.41 and 17.83. According to these comparison results, EBK outperformed OK and IDW in all months. Similarly, OK outperformed IDW.

Table 1. Descriptive statistics of monthly mean rainfall data in Türkiye (mm)

Months	Minimum	Maximum	Mean	Std. Dev.	Skewness	Kurtosis	First Quartile	Median	Third Quartile
January	14	312.5	84.1	52.2	1.4	5.2	43.9	73.8	110
February	14.1	232.8	69.6	39.2	1.1	4.3	38	63.9	89.6
March	21.4	194.4	65.8	28.3	1.1	4.6	44.6	60.4	80.5
April	25.4	161.7	60.0	20.3	1.7	6.5	47.1	54.9	66.2
May	14.2	114.2	50.0	16.8	0.8	4.1	38.8	48.1	59.2
June	1.8	161.6	31.9	22.0	2.1	10.7	18.1	27.5	40.5
July	0	160.1	16.5	20.4	3.6	20.9	4.8	11.3	19.4
August	0	187.1	16.1	24.5	4.2	25.5	4.1	9.1	15.5
September	0.7	282.9	25.4	30.9	4.6	30.7	11.6	16.6	26
October	18.1	317.5	56.9	37.3	3.5	20.4	36.5	46.3	64.4
November	18	255.9	73.0	39.8	1.4	6.0	41.9	65.4	92.6
December	14	324.4	92.9	55.8	1.3	4.9	47.7	81.7	119.8

Table 2. Monthly error and performance metrics of the methods

	EBK			OK			IDW		
Months	MAE	RMSE	R^2	MAE	RMSE	R^2	MAE	RMSE	R^2
January	17.09	24.74	0.813	18.88	27.10	0.749	20.30	28.79	0.722
February	13.96	20.03	0.795	15.27	21.85	0.738	16.35	23.19	0.705
March	11.60	16.08	0.721	12.69	17.86	0.655	13.46	18.66	0.622
April	8.77	12.31	0.638	9.72	13.59	0.557	10.05	14.16	0.524
May	6.20	8.68	0.766	7.33	10.13	0.664	7.39	10.32	0.634
June	5.31	8.26	0.894	6.16	9.43	0.85	6.47	9.75	0.81
July	3.41	6.43	0.906	3.80	7.40	0.873	4.24	8.15	0.841
August	3.49	7.23	0.917	4.14	8.94	0.872	4.36	9.62	0.848
September	4.56	10.61	0.901	5.75	12.45	0.846	6.48	14.67	0.831
October	8.34	14.14	0.857	9.71	16.84	0.797	11.05	19.20	0.736
November	12.99	18.41	0.806	14.55	20.85	0.734	15.83	22.74	0.705
December	17.83	26.03	0.829	20.42	29.06	0.762	21.90	31.22	0.732

Table 3. Monthly precipitation amounts of the basins calculated based on the EBK (mm)

Basin	Area	Months											
	Km^2	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Meriç-Ergene	14510.7	68.6	58.1	58.2	46.3	44.1	42.9	27.6	18.5	35.9	64.5	77.1	79.8
Marmara	23113.7	90.3	72.1	68.3	53.0	41.6	38.4	24.7	28.0	44.7	79.8	92.4	108.9
Susurluk	24304.2	87.6	71.7	65.6	61.1	46.2	30.1	12.9	13.6	27.9	54.1	77.9	97.7
North Aegean	9963.6	100.3	85.9	68.3	53.3	33.9	17.7	6.2	5.7	19.6	49.9	93.3	117.1
Gediz	16981.4	93.9	80.2	65.3	55.4	39.3	19.5	7.9	7.2	16.3	42.4	74.8	101.6
Small Menderes	7027.1	125.6	103.7	77.5	51.9	31.2	10.7	3.1	2.7	14.8	45.8	94.0	132.8
Big Menderes	26017.1	95.5	78.7	64.5	51.9	39.3	20.9	10.6	8.6	14.7	41.8	71.4	99.2
West Mediterranean	21131.2	159.7	114.7	82.2	50.4	32.4	15.1	6.4	4.7	14.1	57.4	105.6	163.6
Antalya	20251.9	169.5	125.9	93.0	71.2	49.0	23.7	9.1	7.7	17.8	70.6	112.9	185.2
Burdur	6273.8	60.8	48.3	47.9	47.3	43.3	26.5	13.9	10.9	15.4	35.6	43.9	60.7
Akarçay	7954.5	48.0	41.3	45.0	50.2	49.1	33.0	14.9	12.7	16.2	38.6	40.2	53.3
Sakarya	63242.9	51.0	40.8	44.7	48.7	48.8	37.4	18.1	16.7	20.1	41.1	42.9	57.8
West Black Sea	28968.4	72.8	54.7	58.9	53.9	57.6	57.1	39.9	43.8	52.9	75.9	70.4	86.7
Yeşilırmak	39620.2	46.7	39.0	48.3	61.6	63.9	46.9	18.3	15.2	26.2	50.3	53.5	52.3
Kızılırmak	82082.5	42.4	33.7	42.3	53.6	56.4	40.4	15.5	13.9	19.8	36.2	39.5	47.4
Konya	49805.3	47.1	37.1	39.5	46.2	44.8	26.6	7.2	5.9	11.4	33.6	41.7	54.5
East Mediterranean	21751.2	118.4	79.4	67.0	46.8	35.5	15.5	5.0	4.0	10.2	49.1	84.7	128.8
Seyhan	22120.8	74.6	59.0	63.2	65.8	58.0	31.2	9.0	8.1	16.9	42.6	59.5	84.9
Asi	7904.2	119.3	105.0	99.9	70.8	50.7	18.3	6.2	7.1	30.0	65.0	87.0	125.4
Ceyhan	21482.6	100.8	83.9	88.5	77.3	58.0	23.8	7.0	5.8	17.9	51.7	75.5	105.4
Euphrates-Tigris	175882	69.9	70.1	75.7	75.3	53.6	17.8	5.4	3.7	9.0	46.4	63.0	74.5
East Black Sea	22876.1	79.5	71.8	70.7	72.7	76.2	79.4	54.9	60.0	77.8	114.2	102.6	92.2
Çoruh	20259.8	40.8	39.5	46.3	58.7	66.9	60.7	39.4	31.9	33.5	56.7	49.9	48.7
Aras	28041.2	23.4	25.6	33.8	52.2	71.6	59.3	40.1	32.0	22.8	43.1	31.7	26.0
Van	17977	40.1	44.4	55.7	69.0	59.6	25.3	11.1	7.1	12.3	49.3	52.6	45.2
Türkiye (total)	780043	70.8	60.2	60.9	60.3	52.4	32.4	15.3	13.8	21.0	50.1	62.6	77.9

Table 4. Monthly precipitation volumes of the basins calculated based on the EBK (billion m^3)

Basin	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1. Meriç-Ergene	1.00	0.84	0.84	0.67	0.64	0.62	0.40	0.27	0.52	0.94	1.12	1.16
2. Marmara	2.09	1.67	1.58	1.23	0.96	0.89	0.57	0.65	1.03	1.84	2.14	2.52
3. Susurluk	2.13	1.74	1.59	1.48	1.12	0.73	0.31	0.33	0.68	1.31	1.89	2.37
4. North Aegean	1.00	0.86	0.68	0.53	0.34	0.18	0.06	0.06	0.20	0.50	0.93	1.17
5. Gediz	1.59	1.36	1.11	0.94	0.67	0.33	0.13	0.12	0.28	0.72	1.27	1.73
6. Small Menderes	0.88	0.73	0.54	0.36	0.22	0.08	0.02	0.02	0.10	0.32	0.66	0.93
7. Big Menderes	2.48	2.05	1.68	1.35	1.02	0.54	0.28	0.22	0.38	1.09	1.86	2.58
8. West Mediterranean	3.37	2.42	1.74	1.07	0.68	0.32	0.14	0.10	0.30	1.21	2.23	3.46
9. Antalya	3.43	2.55	1.88	1.44	0.99	0.48	0.18	0.16	0.36	1.43	2.29	3.75
10. Burdur	0.38	0.30	0.30	0.30	0.27	0.17	0.09	0.07	0.10	0.22	0.28	0.38
11. Akarçay	0.38	0.33	0.36	0.40	0.39	0.26	0.12	0.10	0.13	0.31	0.32	0.42
12. Sakarya	3.23	2.58	2.83	3.08	3.09	2.37	1.14	1.06	1.27	2.60	2.71	3.66
13. West Black Sea	2.11	1.58	1.71	1.56	1.67	1.65	1.16	1.27	1.53	2.20	2.04	2.51
14. Yeşilırmak	1.85	1.55	1.91	2.44	2.53	1.86	0.73	0.60	1.04	1.99	2.12	2.07
15. Kızılırmak	3.48	2.77	3.47	4.40	4.63	3.32	1.27	1.14	1.63	2.97	3.24	3.89
16. Konya	2.35	1.85	1.97	2.30	2.23	1.32	0.36	0.29	0.57	1.67	2.08	2.71
17. East Mediterranean	2.58	1.73	1.46	1.02	0.77	0.34	0.11	0.09	0.22	1.07	1.84	2.80
18. Seyhan	1.65	1.31	1.40	1.46	1.28	0.69	0.20	0.18	0.37	0.94	1.32	1.88
19. Asi	0.94	0.83	0.79	0.56	0.40	0.14	0.05	0.06	0.24	0.51	0.69	0.99
20. Ceyhan	2.17	1.80	1.90	1.66	1.25	0.51	0.15	0.12	0.38	1.11	1.62	2.26
21. Euphrates-Tigris	12.29	12.33	13.31	13.24	9.43	3.13	0.95	0.65	1.58	8.16	11.08	13.10
22. East Black Sea	1.82	1.64	1.62	1.66	1.74	1.82	1.26	1.37	1.78	2.61	2.35	2.11
23. Çoruh	0.83	0.80	0.94	1.19	1.36	1.23	0.80	0.65	0.68	1.15	1.01	0.99
24. Aras	0.66	0.72	0.95	1.46	2.01	1.66	1.12	0.90	0.64	1.21	0.89	0.73
25. Van	0.72	0.80	1.00	1.24	1.07	0.45	0.20	0.13	0.22	0.89	0.95	0.81
Türkiye (total)	55.23	46.96	47.50	47.04	40.87	25.27	11.93	10.76	16.38	39.08	48.83	60.77

In the last step of the paper, monthly precipitation potentials of watersheds were computed on the EBK-based, which provided the best accomplishment. Firstly, the watersheds were sorted out one by one from the monthly precipitation distribution maps created for Türkiye, and monthly average areal precipitation amounts were calculated. Then, the average precipitation amounts (heights) of the watersheds were multiplied by their surface areas, and the precipitation volumes were calculated. These processes were repeated each month.

When monthly average areal rainfall amounts of Türkiye were analyzed, it was found that the highest rainfall amounts were observed in December (77.9 mm) and January (70.8 mm), and the lowest rainfall amounts were observed in August (13.8 mm), and July (15.3 mm) (Table 3). The rainfall amounts for November (62.6 mm), February (60.2 mm), March (60.9 mm), and April (60.3 mm) were very close to each other. Similarly, the rainfall amounts for May (52.4 mm) and October (50.1 mm) were also very close to each other.

Major differences were determined in monthly precipitation models and potentials of the watersheds. The watersheds with the highest rainfall amounts by month were Antalya (185.2 mm, 169.5 mm, 125.9 mm), West Mediterranean (163.6 mm, 159.7 mm, 114.7 mm), and Small Menderes (132.8 mm, 125.6 mm, 103,7 mm) in December, January, and February; Asi (99.9 mm), Antalya (93.0 mm), and Ceyhan (88.5 mm) in March; Ceyhan (77.3 mm), Euphrates-Tigris (75.3 mm) and East Black Sea (72.7 mm) in April. Between May and September, the highest rainfall amounts were observed in Northern Türkiye, particularly in the East Black Sea, followed by Aras, Çoruh, West Black Sea, and Marmara. In October, the watersheds with the most precipitation amounts were again Antalya (112.9 mm), West Mediterranean (105.6 mm), and East Black Sea (102.6 mm).

The watersheds with the lowest rainfall amounts by month were Aras in January (23.4 mm), February (25.6 mm), March (33.8 mm), November (31.7 mm), and December (26.0 mm); Konya in April (46.2 mm) and October (33.6 mm); Small Menderes in May (31.2 mm), June (10.7 mm), July (3.1 mm) and August (2.7 mm), and Tigris-Euphrates in September (9.0 mm).

Mean areal precipitation was found over 100 mm in December in nine watersheds, in January in seven, in February in four, in November in three, and in March and October in one watershed. On the other hand, the monthly average rainfall amounts of 13 watersheds in August and 11 watersheds in July were below 10 mm. In June, July, August, and September, the amount of rainfall was very little in all watersheds other than those in Northern Türkiye (Table 3; Figure 5).

Some watersheds differ from others in terms of the months in which they receive the highest rainfall amounts. These watersheds are Tigris-Euphrates (75.7 mm) in March, Van (69.0 mm) in April, Aras (71.6 mm), Çoruh (66.9 mm), Yeşilırmak (63.9 mm), and Kızılırmak (56.4 mm) in May. Among all watersheds, the greatest rainfall magnitude was in December (Antalya: 184.4 mm, Aras: 26.4 mm), and the month with the lowest magnitude was April (Ceyhan: 76.7 mm, Konya: 46.1 mm).

The months with the highest volume of rainfall in the entire of Türkiye were December (60.77 billion m^3), January (55.23 billion m^3), and November (48.83 billion m^3). The rainfall volume for February, March, and April was approximately 47 billion m^3. The total rainfall volume for the month with the lowest rainfall, August, was calculated as 10.76 billion m^3. This volume was 11.93 billion m^3 in July and 16.38 billion m^3 in September (Table 4).

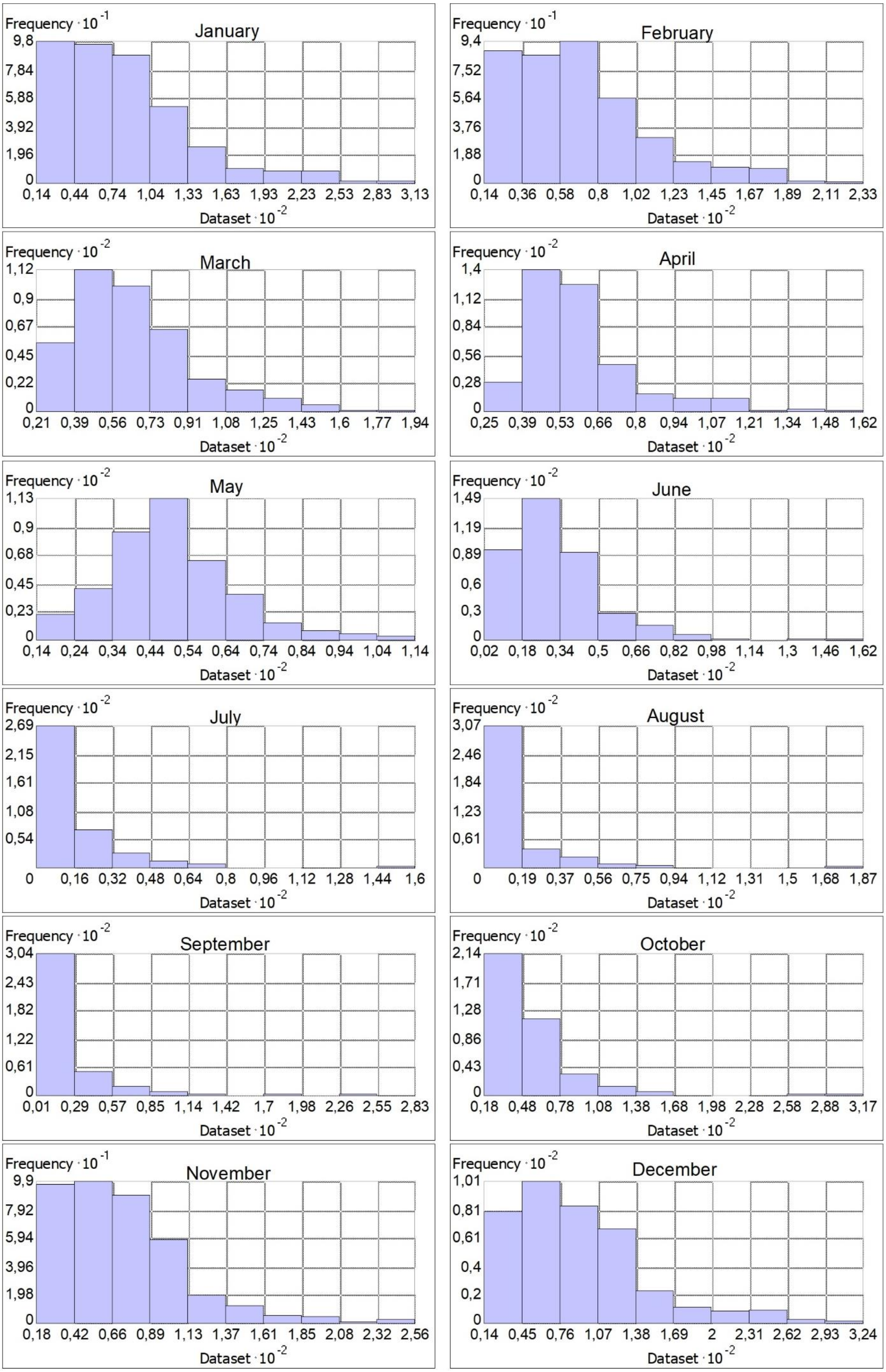

Figure 2. Monthly mean rainfall histograms of the rain gauge stations

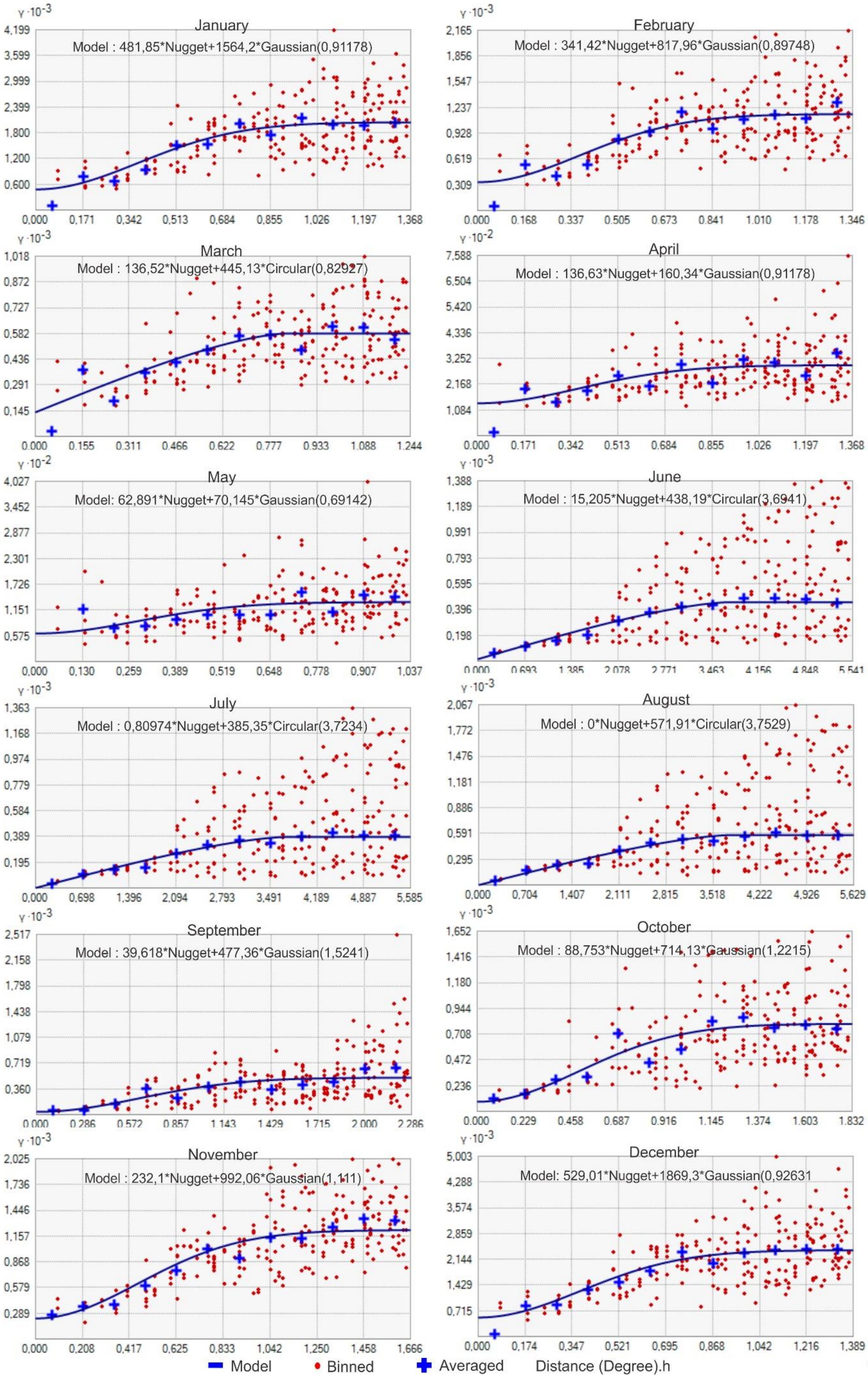

Figure 3. Models and parameters of experimental and theoretical semi-variogram for OK

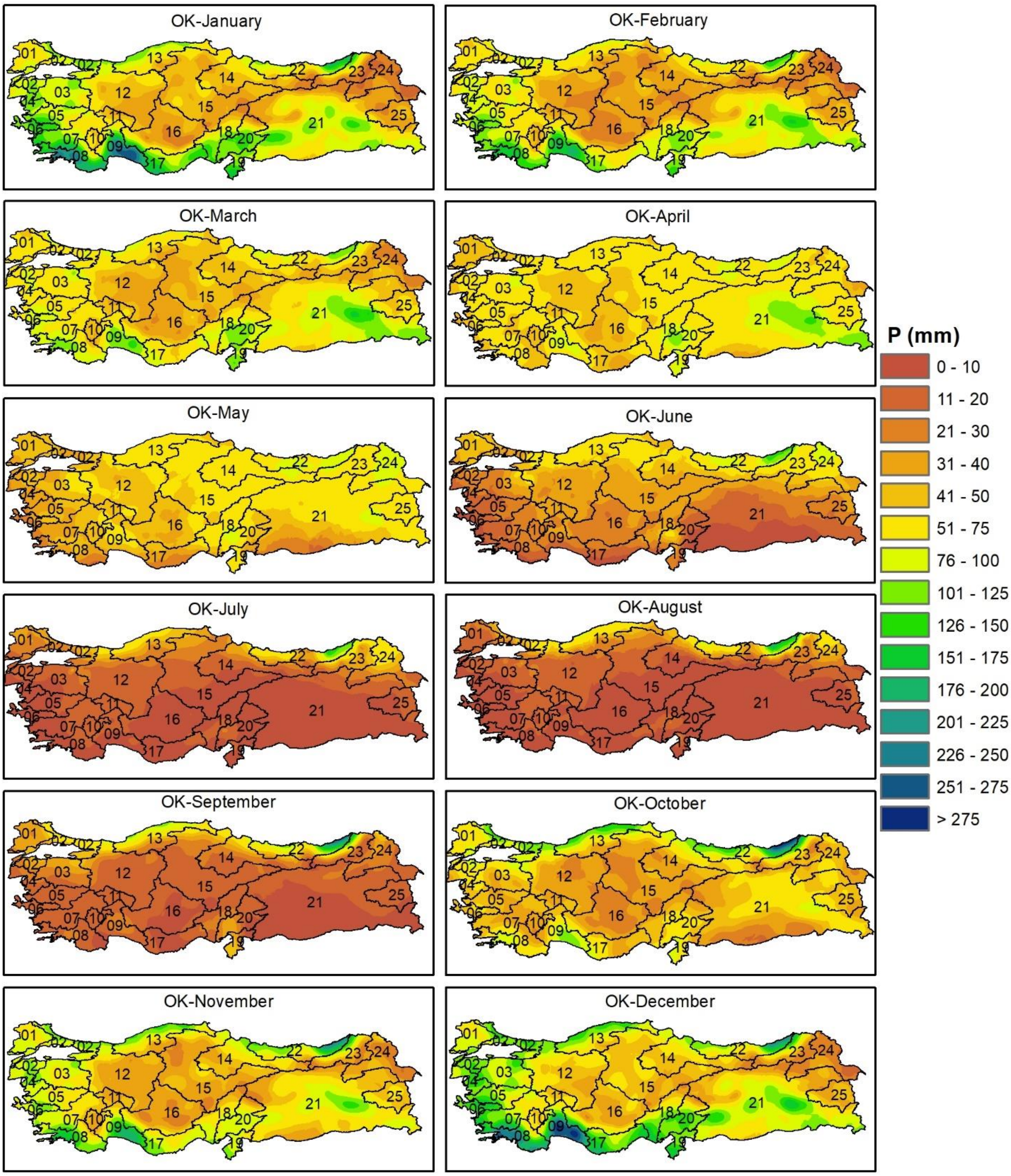

Figure 4. OK-based monthly precipitation distribution map of the basins

The watersheds with the greatest volume of rainfall were Tigris-Euphrates from October to May, Kızılırmak in June and July, and East Black Sea in August and September. The watersheds with the lowest volume of precipitation were Burdur from September to April and Small Menderes from May to August.

Discussion and Conclusions

Precipitations are considered more significant than other meteorological elements since they constitute the primary resource of fresh water, which is scarce and irreplaceable for life. In Türkiye, one of the water-scarce countries, where water resources depend on local rainfalls, it is crucial to determine the most real-like precipitation pattern and calculate the precipitation amount and volume.

The watershed-scale water administration is one of the necessary instruments for both the protection and sustainable use of water resources. Türkiye has been trying to transition to a watershed-scale water administration strategy. In the paper, the monthly precipitation distribution maps of 25 main watersheds in Türkiye were modeled, and the precipitation amounts and volumes were calculated.

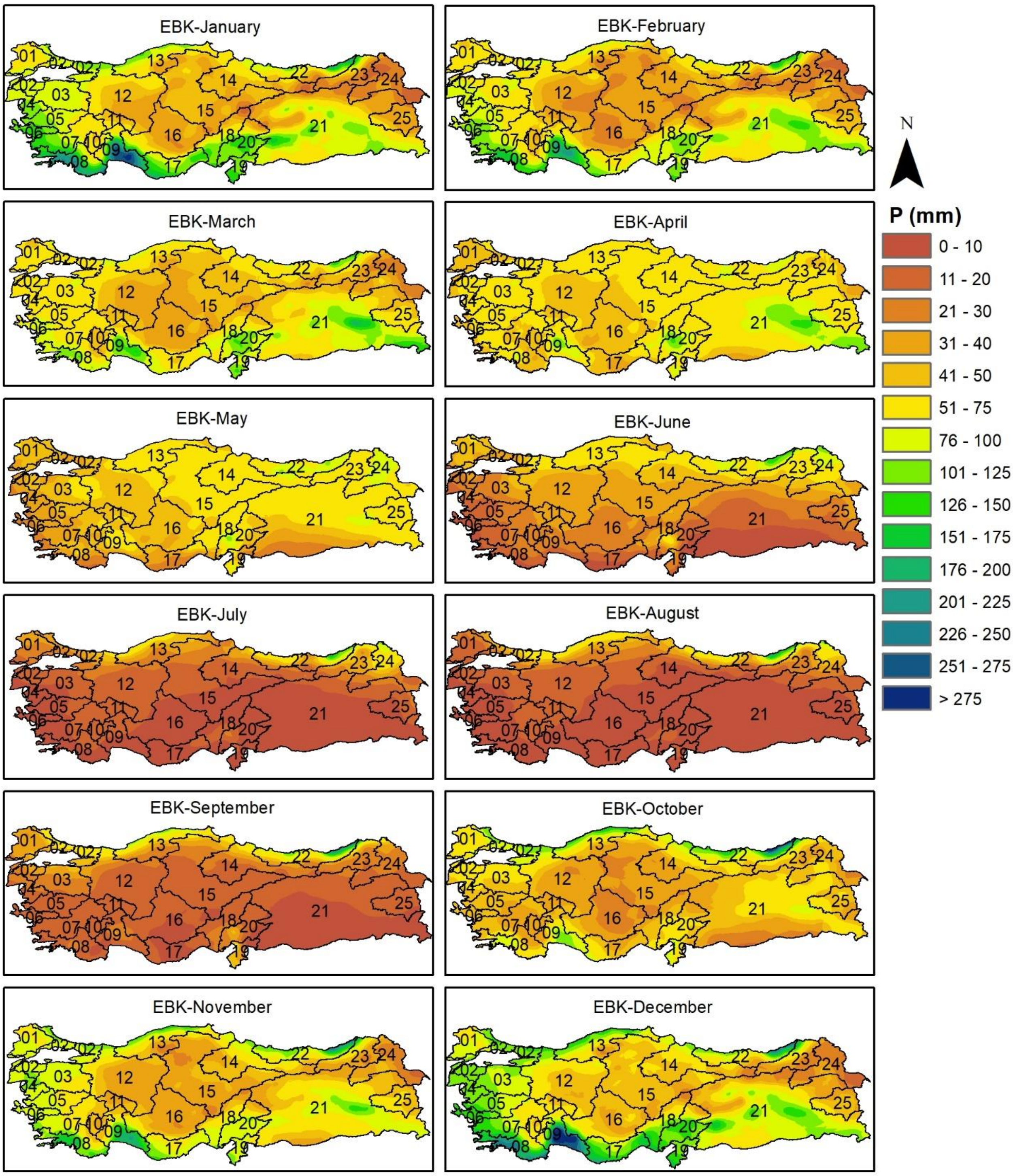

Figure 5. EBK-based monthly precipitation distribution map of the basins

The monthly precipitation data of 137 SHW raingauges, in addition to 254 SMS raingauges for the period between 1965 and 2018 were used. By combining the data of these two institutions, both the number of rain gauges required by WMO standards was achieved, and data frequency and homogeneity were ensured. Two geostatistical methods, EBK and OK, and a deterministic IDW method were used, and their performances were evaluated through cross-validation. Although all three methods showed high cross-verification performances, EBK outperformed OK and IDW in all 12 months. Similarly, OK outperformed IDW.

The months, in which the three methods showed high or low performances, were found to be parallel. RMSE and MAE amounts were low in low-precipitation months (such as July and August), and high in high-precipitation months (such as December and January). These findings are in accordance with (Pellicone et al., 2018). All three methods showed the lowest R^2 performances in April and the highest R^2 performances in July and August.

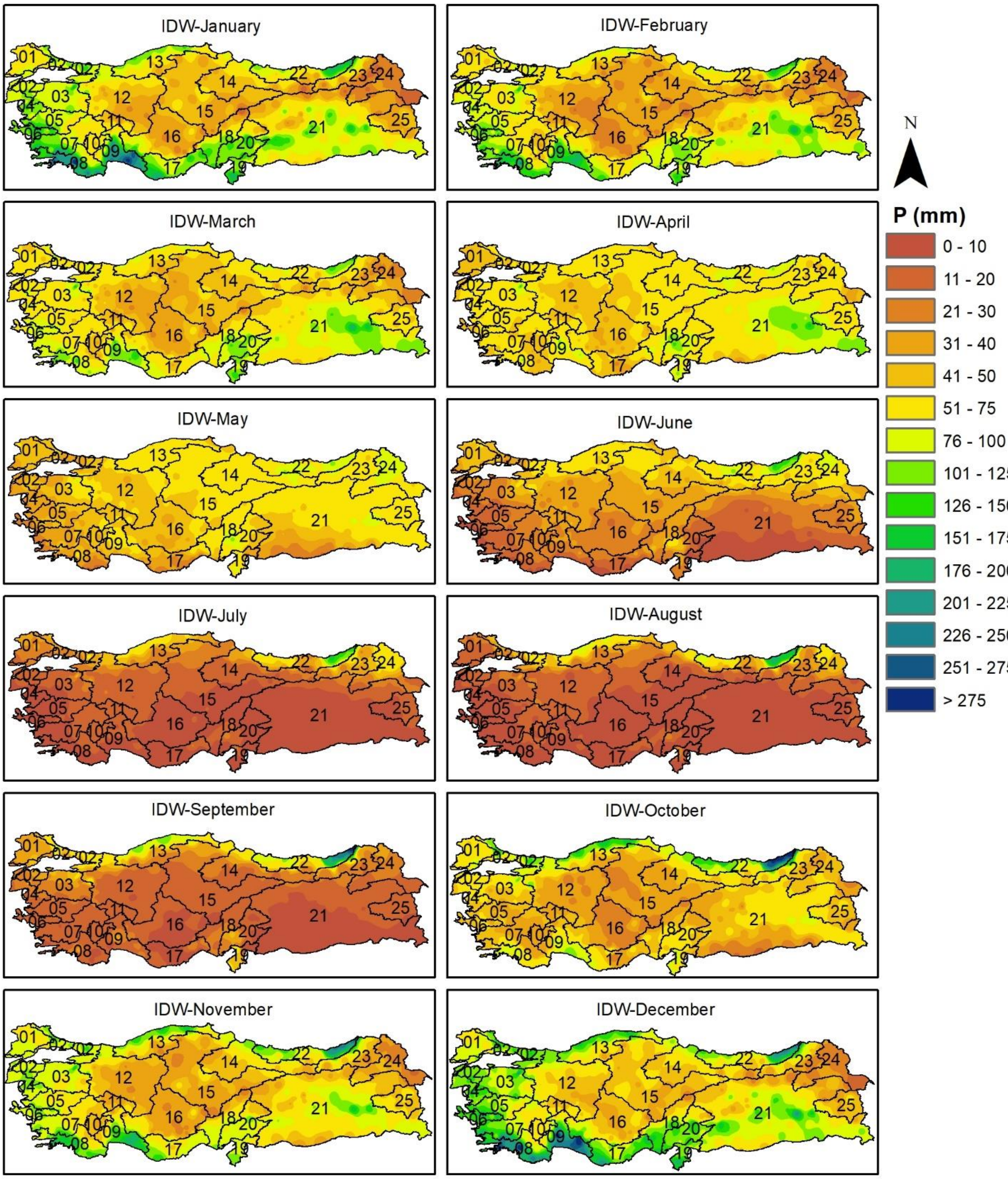

Figure 6. IDW-based monthly precipitation distribution map of the basins

Considering the high variability of the spatial distribution of monthly precipitations in Türkiye, the performances of OK and IDW methods are also adequate (Moriasi et al., 2007). The increased number of stations also increased the performance of these methods (Dirks et al., 1998; Borges et al., 2016; Frazier et al., 2016; Hurtado et al., 2021; Aksu, 2021, Aksu, 2023).

The months with the highest rainfall potential in Türkiye are December (77.9 mm, 60.77 billion m^3) and January (70.8 mm, 55.23 billion m^3) and the months with the lowest rainfall potential are August (13.8 mm, 10.76 billion m^3), July (15.3 mm, 11.93 billion m^3), and September (21.0 mm, 16.38 billion m^3). The precipitation potentials of November (62.6 mm, 39.08 billion m^3), February (60.2 mm, 46.96 billion m^3), March (60.9 mm, 47.5 billion m^3), and April (60.3 mm, 47.04 billion m^3) were almost equal. Similarly, the precipitation potentials of May (52.4 mm, 40.87 billion m^3) and October (50.1 mm, 39.08 billion m^3) were also very close to each other.

The watersheds receiving the highest rainfall amounts between November and April are located in the south and west of Anatolia and have a coast on the Mediterranean and the Aegean Seas. Antalya in November (112.9 mm), December (185.2 mm), January (169.5 mm), and February (125.9 mm), Asi in March (99.9 mm), and Ceyhan in April (77.3 mm) are the watersheds with highest average rainfall amounts. The watershed with the highest amount of rainfall between May and October is the East Black Sea located in Northern Türkiye. On the other hand, the watersheds with the lowest rainfall amounts are Aras (between November and March), Konya (in April and October), Small Menderes (between May and August), and Tigris-Euphrates (in September).

It was determined that precipitation in Türkiye showed great differences from basin to basin within and between months. There are two main factors affecting the monthly precipitation amount and distribution of the Basins in Türkiye. The first is air masses affecting Türkiye, the second is its topographic features. Türkiye is not located in the source region of air masses. It is under the influence of weather conditions coming from different source regions according to seasons and months. Generally, it is under the influence of tropical air masses between May and October, and polar air masses between November and April (Türkeş, 2020a).

When polar air masses moving from north to south between November and April meet with tropical air masses over the Mediterranean basin, they form the Mediterranean front system (Türkeş, 2010). Cyclones, especially over the Eastern Mediterranean, bring abundant rainfall to the basins in the south and west of Türkiye, both frontal and orographically. The cyclones can penetrate the inner and eastern basins of the country, weakening by the effect of the topography. On the other hand, the air masses that come from over the Black Sea to Türkiye pick moisture and cause both frontal and orographic precipitation over the basins located in the north of the country in 12 months of the year.

Monthly precipitation amounts were found to be more regular in 12 months of the year in the East Black Sea, Aras, Çoruh, West Black Sea, and Marmara watersheds located in Northern Anatolia. The monthly rainfall amounts of the remaining 20 watersheds are extremely irregular. In the south and west of the country, the watersheds flowing into the Mediterranean and Aegean Seas, the amounts of precipitation in December exceeded 100 mm, and in August precipitation was below 10 mm.

In May, June, July, August, and September, when water, particularly agricultural irrigation, is required the most, all watersheds, except for the ones located in Northern Türkiye, are affected by the Asiatic Monsoon low-pressure system and go through a drought. These findings of the study are consistent with the previous studies Türkeş, (2010; 2020a), Hoekstra et al., (2012), and Mekonnen and Hoekstra (2016).

The use of the TSHW station data has modified the monthly rainfall models of the watersheds in Türkiye. The obtained rainfall models differ from the previous studies for Türkiye (Atalay, 2010). In the interpolation of meteorological parameters, the EBK technique should also be considered.

The pressure on the freshwater resources in Türkiye's watersheds may continue to increase in the future due to an increase in agricultural irrigation and climate change. Planning water consumption in line with the rainfall pattern and potential of the watersheds can play a key role in coping with increasing water scarcity.

The monthly precipitation potential of Türkiye is also crucial for the Middle East and its neighboring countries.

Annual evaluations of the precipitation distribution can hide the changes within the year, so it is important to prepare precipitation models monthly. For example, in Antalya and the West Mediterranean watersheds, which are among the wettest watersheds of Türkiye on an annual basis (Aksu, 2021), there is a shortage of precipitation in six months of the year.

The monthly green and blue water footprints of the Watersheds in Türkiye should be determined.

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