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Estimation of standard duration maximum rainfall by using regression models

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Abstract: Gauging stations of meteorological networks generally record rainfall on a daily basis. However, sub-daily rainfall observations are required for modelling flood control structures, or urban drainage systems. In this respect, determination of temporal distribution of daily rainfall, and estimation of standard duration of rainfall are significant in hydrological studies. Although sub-daily rainfall gauges are present at meteorological networks, especially in the developing countries, their number is very low compared to the gauges that record daily rainfall.

This study aims at developing a method for estimating temporal distribution of maximum daily rainfall, and hence for generating maximum rainfall envelope curves. For this purpose, the standard duration of rainfall was examined. Among various regression methods, it was determined that the temporal distribution of 24-hour rainfall successfully fits the logarithmic model. The logarithmic model's regression coefficients (named *a* and *b*) were then linked to the geographic and meteorological characteristics of the gauging stations. The developed model was applied to 47 stations located at two distinct geographical regions: the Marmara Sea Region and Eastern Black Sea Region, Turkey. Various statistical criteria were used to test the method's accuracy, and the proposed model provided successful results. For instance, the *RMSE* values of the regression coefficients *a* and *b* in Marmara Regions are 0.004 and 0.027. On the other hand, *RMSE* values are 0.007 and 0.02 for Eastern Black Sea Region.

Keywords: Eastern Black Sea Region, Marmara Region, regression model, standard duration maximum rainfall, temporal distribution of maximum daily rainfall

INTRODUCTION

Maximum rainfall data is required in many studies on water resources and hydrology such as flood control structures, development of rainfall-runoff models, watershed modelling, and storm water drainage projects. Maximum rainfall data is used in these studies on a daily basis, whereas some studies require sub-daily data. Simulation models for watershed hydrology typically require sub-daily rainfall data such as hourly measurements. MELSEN *et al.* [2016] had provided a summary of different catchment sizes, and of corresponding temporal resolutions. For the simulation of instantaneous flood peaks of the catchments of a few hundred square kilometers, hourly rainfall durations are required [MÜLLER *et al.* 2018]. Similarly, in urban hydrology applications, short-duration rainfall needs to be identified or predicted [ALY *et al.* 2009; BORGA *et al.* 2005; EGODAWATTA *et al.* 2007]. For instance, in the design of urban drainage systems, the basin size is generally small (several hectares), and consequently the basin response time is very short, and therefore relatively shorter duration rainfall data (e.g., 10–15 min.) suits the hydrological and hydraulic models [HADDAD, RAHMAN 2014].

Globally, it is clear that the non-recording (daily) type rain gauge network has a much higher presence and longer recording years than the recording (sub-daily) type rain gauge network. In the United States, the number of past daily rainfall records is nearly three times the sub-daily rainfall records [BONNER 1998]. The Australian Bureau of Meteorology had stated [2003] that the number of daily rainfall records in Australia is much higher than the number of sub-daily rainfall records. The number of daily rainfall gauging stations in Turkey is almost ten times the sub-daily rainfall gauging stations.

For many years, the lack of recording the measurements has forced the researchers to develop methods for predicting sub-daily rainfall from daily data. For this purpose, many studies had been carried out for parsing out the daily rainfall data [Chio *et al.* 2008; Glasbey *et al.* 1995; Gupta, Waymire 1993; Gyasi-Agyei 2005; Hingray, Haha 2005; Koutsoyiannis *et al.* 2003; Koutsoyiannis, Onof 2001; Molnar, Burlando 2005; Müller-Thomy *et al.* 2018; Olsson 1998; Olsson, Berndtsson 1998; Ormsbee 1989; Schertzer, Lovejoy 1987; Socolofsky *et al.* 2001; Veneziano *et al.* 1996]. A few studies had also suggested empirical relationships for estimating short-duration rainfall from daily rainfall [Al Mamun *et al.* 2018; Chowdhury *et al.* 2007; Haddad, Rahman 2014]. The spatial and temporal variations of rainfall had also been investigated for different regions of Turkey [Erbekçi 2006; Hadi, Tombul 2018; Irdem 2005; Kadioglu, Şen 1998; Türkeş *et al.* 2007; Yozgatligil, Türkeş 2018].

This study intends to obtain sub-daily (short-duration) rainfall data using the Multiple Linear Regression model. For this purpose, the rainfall measurement records (standard-durations: 5-, 10-, 15-, 30-min., 1-, 2-, 3-, 4-, 6-, 12-, 18-, 24-hours maximum rainfall data) of two different regions of Turkey, as being the Marmara and the Eastern Black Sea Regions, were used. First, envelope curves consisting of pluviograph ratios for each station were determined for both regions. Then, the logarithmic models that conformed successfully to envelope curves, and the regression coefficients of the logarithmic curves (*a*, *b*) were obtained. The statistical analysis revealed that the regression coefficients had significant relationship with specific geographical and meteorological features of the regions covered by the study. This way, standard duration rainfall amounts could be estimated by the present daily rainfall data.

STUDY MATERIALS AND METHODS

THE STUDY APPROACH

In this study, the annual maximum rainfall data for specific time intervals (5-, 10-, 15-, 30-min, 1-, 2-, 3-, 4-, 5-, 6-, 8-, 12-, 18-, and 24-h) was used to identify the temporal distribution, and the envelope curve of the rainfall. In order to determine the relationship between maximum rainfall and time, various models were tested. The logarithmic model was found to be the most appropriate one for the data. The logarithmic conformity provides a coefficient (*a*), and a residual term (*b*). In the next step, by using multiple linear regression (MLR), the relationships between the regression coefficients (*a*, *b*; dependent variables, predictands), and meteorological and geographical data (independent variables, predictors) were obtained. The methodology, suggested by this study, was applied to datasets obtained from two different regions in Turkey. The procedure was performed in the calibration stage for each station as follows:

– calculation of the average annual maximum rainfall of standard durations;
– determination of the standard duration maximum rainfall's (SDMR) envelope curve (having logarithmic conformity);
– application of the stepwise MLR on the regression coefficients (*a*, *b*), and the meteorological and geographical data (predictors): calibration step by using the stations in the Marmara Region;
– model validation, and estimation of SDMR envelope curve (Marmara Region);
– application of the model's procedures on the stations located in the Eastern Black Sea Region;
– assessment of the model's accuracy by using the criteria of mean relative error (*MRE*), root mean square error (*RMSE*), and Nash-Sutcliffe model efficiency (*NSE*) coefficient of the observed and predicted regression coefficients.

STANDARD DURATION MAXIMUM RAINFALL'S TEMPORAL DISTRIBUTION

The annual maximum rainfall represents an essential criterion for hydraulic structure and drainage system design. This study reveals both the magnitude and temporal distribution of maximum rainfall as key indicators of rainfall hazards. The approach consists of calculating the average of standard duration maximum rainfalls (5-, 10-, 15-, 30-min, 1-, 2-, 3-, 4-, 5-, 6-, 8-, 12-, 18-, and 24-h) during the recording period. In other words, it was intended to obtain an indicator that represents the maximum rainfall data variation regarding the rainfall duration.

STANDARD DURATION MAXIMUM RAINFALL'S ENVELOPE CURVE

In this study, the logarithmic conformity was employed for providing a relationship between the standard duration maximum rainfall, and pluviograph rates. The envelope curve is a linear least squares regression tool that fits the distribution of data. The logarithmic curves obtained can be expressed as follows:

$$P_d = P_{24}\left[a \ln\left(\frac{d}{24}\right) + b\right] \tag{1}$$

where: P_d represents the average of annual maximum rainfalls for a specific time interval, P_{24} is the average of annual maximum rainfalls for the 24-hour duration, and d is the duration of rainfall (5-, 10-, 15, 30-min, 1-, 2-, 3-, 4-, 5-, 6-, 8-, 12-, 18-, and 24-hours).

The preference of the logarithmic conformity is based on the values of the coefficient of determination (R^2).

STEPWISE MULTIPLE LINEAR REGRESSION

After identifying the best fit's envelope curve, the regression coefficients (*a*, *b*) obtained were considered as dependent variables for the MLR. The MLR, in general, is a powerful tool for determining relationships between predictands and predictors. The linear regression model can be expressed as follows:

$$y = \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 + \ldots + \alpha_n x_n + \varepsilon \tag{2}$$

where: y is the dependent variable, x_1, x_2, …, x_n are the independent variables, α_1, α_2, …, α_n are the regression coefficients, and ε represents the model's residual.

The regression model is run for a confidence interval of 95%. The null hypothesis (H_0) of the MLR states the regression coefficient as $\alpha_i = 0$, while the alternative hypothesis (H_1) states it as $\alpha_i \neq 0$. The significance of regression coefficients can be checked via p-value which expresses the probability that the test statistics will get a value as extreme as the value observed. And it is assumed that the alternative hypothesis is false. If the p-value is less than 0.05, the alternative hypothesis is then accepted.

EVALUATION INDICATORS

In this study, three statistical indicators were used to scientifically evaluate the performance of the regression model. The model's evaluation covered the use of mean relative error (*MRE*), root mean square error (*RMSE*), and the Nash–Sutcliffe model efficiency (*NSE*) coefficient.

The accuracy of the regression model was evaluated by calculating the *MRE*:

$$MRE = \frac{1}{n}\sum_{i=1}^{n}\frac{|a_i - a_i^{'}|}{|a_i|} \tag{3}$$

where: a_i is the original regression coefficient, and a_i' is the predicted regression coefficient. In addition, the *RMSE* was calculated to evaluate the model's ability to track high values:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(a_i^{'} - a_i\right)^2}{n}} \tag{4}$$

Moreover, the *NSE* was calculated in order to detect the deviation between model's predictions, and its mean. These statistical criteria have a wide range of applications for hydrological model calibrations [Lin *et al.* 2017]. The *NSE* coefficient was obtained as follows:

$$NSE = 1 - \sqrt{\frac{\sum_{i=1}^{n}\left(a_i^{'} - a_i\right)^2}{\sum_{i=1}^{n}\left(a_i - \bar{\alpha}\right)^2}} \tag{5}$$

where: $\bar{\alpha}$ is the mean of the original regression coefficient.

STUDY AREA AND DATASET

The Marmara Region is located in the north western part of Turkey and covers an area of approximately 67,000 km^2 (Fig. 1). Geographically, it is located on both the Asian and the European Continents. Despite the mild Mediterranean climate in the region, characteristics of continental climate are also observed in the interior parts. In Marmara Region, summers are warm and humid, while winters are cold and wet with occasional snowstorms. The coldest month of the year is January with a monthly mean temperature of 4.7°C, while the maximum monthly mean temperatures occur in July, about 23.5°C. The region receives an average rainfall of 665 mm annually with high spatial variability. The annual rainfall exceeds 800 mm in the eastern part of the region, whereas it is less than 600 mm in the central and western parts [Kömüşçü, Çelik 2012].

Meteorological data obtained from 32 recording stations, being operated by the Turkish State Meteorological Service, was used in this study (Tab. 1).

The Eastern Black Sea Region is located in the northeast of Turkey (Fig. 1). High mountain ranges run parallel to the sea coast as the north boundary of the study area, and they reach to an altitude of approximately 3000 m. The Black Sea Region has a steep, rocky coast with some rivers that cascade through the coastal ranges' straits. The difference in temperature between summer and winter is low. Summers are generally warm, and winters are cool in the coastal part, whereas it is snowy and cold at higher elevations. January and July are the coldest and warmest months with an average temperature of 4.2°C and 22.1°C, respectively. The region's average rainfall is above 925 mm, and varies between 681 mm and 2276 mm. The annual average humidity rate is about 76% to 77%. Meteorological data of 15 gauging stations was used in this study. The meteorological and geographical features of the stations located in the Eastern Black Sea Region are given in Table 1.

Homogenous regions were identified considering annual total rainfall values by using cluster analysis suggested by Firat *et al.* [2012]. According to the results of the study, it was determined that Marmara and the Eastern Black Sea Regions have different meteorological characteristics. It is crucial to note that Marmara and the Eastern Black Sea Regions have distinct geographical features. The mean altitude is 280 m in Marmara Region, and 1163 m in the Eastern Black Sea Region. The Eastern Black Sea Region's average inclination is two times than that of the Marmara Region [Elibüyük, Yilmaz 2010].

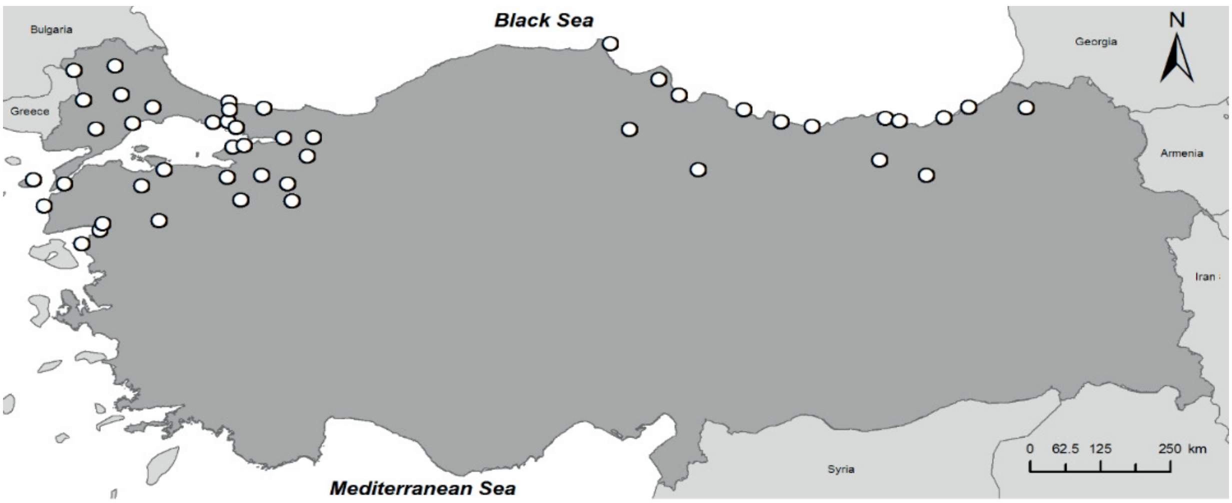

Fig. 1. Location of the meteorological stations used in this study; source: own study

Table 1. Features of the meteorological stations in the study areas

Station name	Latitude (N)	Longitude (E)	Elevation (m)	Mean pre-cipitation (mm)	Mean temperature (°C)	Relative humidity (%)
Marmara Region						
Ayvalik	39.3	26.7	4	641	16.8	70
Balikesir Hav.	39.6	27.9	102	579	14.5	70
Bandirma	40.3	28	63	703	15.0	73
Bilecik	40.1	30	539	445	12.4	68
Bozcaada	39.8	26.1	30	525	15.4	76
Bozuyuk	39.9	30.1	754	483	10.6	71
Burhaniye	39.5	27	20	633	15.9	60
Bursa	40.2	29	100	704	14.5	68
Canakkale	40.1	26.4	6	613	14.9	73
Cinarcik	40.6	29.1	16	897	14.9	73
Corlu	41.2	27.8	145	567	12.8	77
Edirne	41.7	26.6	51	593	13.6	70
Edremit	39.6	27	21	705	16.5	59
Florya	41.0	28.8	37	646	14.1	74
Geyve	40.5	30.3	100	619	13.7	74
Gokceada	40.2	25.9	79	742	15.2	67
Gonen	40.1	27.6	37	683	14.1	72
Kadikoy	41.0	29	5	676	14.1	75
Istanbul Bolge	40.9	29.2	18	664	15.0	73
Keles	39.9	29.2	1 063	758	9.5	63
Kirklareli	41.7	27.2	232	562	13.2	70
Kocaeli	40.8	29.9	74	791	14.6	72
Kumkoy	41.3	29	38	794	13.9	78
Luleburgaz	41.4	27.3	46	592	13.1	71
Malkara	40.9	26.9	207	717	13.3	70
Sakarya	40.8	30.4	30	820	14.4	73
Sariyer	41.1	29.1	59	806	13.8	77
Sile	41.2	29.6	83	818	13.5	77
Tekridag	41.0	27.5	4	577	13.9	77
Uzunkopru	41.3	26.7	45	658	13.5	72
Yalova	40.7	29.3	4	750	14.5	75
Yenisehir	40.3	29.6	238	517	13.1	70
Eastern Black Sea Region						
Akçaabat	41.03	39.56	9	723	14.2	74
Artvin	41.18	41.82	612	703	12.0	74
Bafra	41.55	35.92	107	790	13.6	74
Bayburt	40.25	40.22	1 582	432	6.8	54
Giresun	40.92	38.39	90	1 246	14.4	74
Gümüshane	40.46	39.47	1 219	457	9.5	64
Merzifon	40.88	35.46	763	410	11.5	67
Ordu	40.98	37.89	7.62	1 028	14.1	73
Pazar	40.23	36.30	1 024	2 021	13.3	72
Rize	41.04	40.50	7.62	2 276	14.2	77
Samsun	41.34	36.26	4.27	701	14.4	73
Sinop	42.03	35.15	28.6	681	14.0	74
Tokat	40.33	36.56	613	435	12.8	63
Trabzon	41.00	39.76	38	811	14.2	71
Ünye	41.14	37.29	19	1 156	14.2	76

Source: own study.

RESULTS AND DISCUSSION

TEMPORAL DISTRIBUTION OF MAXIMUM DAILY RAINFALL

The suggested approach was applied at 47 meteorological stations located in Marmara and the Eastern Black Sea Regions. Firstly, during the recording period, the average annual maximum rainfall (P_d) for standard durations was calculated. Then, the envelope curves (P_d/P_{24} versus $d/24$) of each station were obtained, and expressed according to Equation (1). To give an idea, the envelope curves of Malkara Station located in Marmara Region, and of Giresun Station located in the Eastern Black Sea Region are depicted in Figure 2. Similar to Malkara and Giresun Stations, other stations' envelope curves had indicated that approximately 80% of the rainfall occurs in the first 12 hours of the day. This finding can be useful for planning water retaining structures in a riverine environment, and for planning water drainage systems in an urban environment. The relation between the maximum rainfall and its duration is critical for flood prevention design. Several models were utilized to fit the envelope curves. However, the most suitable model for all the stations was determined as the logarithmic conformity.

For each station, the regression coefficients (a, b) were obtained from the logarithmic models. For stations located in the Marmara Region, the regression coefficient (a) varied between 0.128 and 0.162 with an average of 0.144, and the regression coefficient (b) varied between 0.813 and 0.965 with an average of 0.903. For stations located in the Eastern Black Sea Region, the regression coefficient (a) varied between 0.121 and 0.159 with an average of 0.145, and the regression coefficient (b) varied between 0.819 and 0.966 with an average of 0.949. The average coefficients of determination (R^2) for the envelope curves obtained from Marmara and the Eastern Black Sea Regions were 0.973 and 0.966, respectively.

IDENTIFICATION OF MODEL PREDICTORS

This study's main purpose is to obtain the standard duration maximum rainfall's envelope curves for locations lacking measurements of rainfall standard duration. SDMR's envelope curves were developed by a regression model where the inputs were meteorological and geographical datasets. The logarithmic conformity coefficients of each station were used in the multiple linear regression equation where the meteorological data (annual total rainfall, monthly maximum rainfall, average temperature, minimum temperature, maximum temperature, and average relative humidity), and geographical data (latitude, longitude, altitude, and distance from the sea) were predictors. In this step, the stepwise MLR was used to eliminate the predictors with coefficients beyond the confidence level (95%). By the linear relationship obtained between the logarithmic model coefficients (a, b), and the meteorological and geographical variables, it is possible to obtain the envelope curves of standard duration maximum rainfall. The linear relationship for the regression coefficient (a) for Marmara Region depends on the monthly maximum rainfall, and the yearly total rainfall (Tab. 3).

Then again, the linear relationship for the regression coefficient (b) for both the Marmara Region and Eastern Black Sea Region depends on latitude, longitude, and monthly maximum rainfall (Tab. 3). Briefly, the regression coefficient (a) is associated to meteorological features, and the regression coefficient (b) is related to both the meteorological and geographical features. The p-value should be less than 0.05 at the confidence level of 95%. It is essential to mention that the model input coefficients displayed statically significant values where the p-value was lower than 0.05.

The models were calibrated for 27 stations located in Marmara Region. In order to evaluate the model's accuracy, *MRE*, *RMSE*, and *NSE* were calculated (Tab. 5).

The model's validation step was performed for 5 stations located in Marmara Region. The linear relationship between the regression coefficients (a, b), and the model's predictors was used to predict the values of regression coefficients. Then, the standard duration maximum rainfall's (*SDMR*) envelope curves were obtained (Fig. 3).

The model's calibration and validation were performed for the stations located in Marmara Region. The model's procedures were also applied to stations located in the Eastern Black Sea Region for verifying the efficiency of approach. Similar to

Table 3. Coefficients and p-values of the regression model for Marmara and the Eastern Black Sea Regions

Regression parameters	Marmara Region		Eastern Black Sea Region	
	coefficients	p-value	coefficients	p-value
***a*-coefficient**				
Intercept	0.10377	9.04E−17	0.1192	9.89E−11
Yearly total precipitation	−0.00002	0.03284	−0.00001	0.02558
Monthly maximum precipitation	0.00101	6.41E−10	0.00069	0.02190
***b*-coefficient**				
Intercept	1.37581	0.01099	1.80105	0.28163
Latitude	−0.00271	0.00811	−0.00861	0.00202
Longitude	−0.01353	0.03179	−0.00879	0.00129
Elevation	−0.00001	0.00714	−0.00007	0.00287
Monthly maximum precipitation	0.00042	0.00687	0.00015	0.00381

Source: own study.

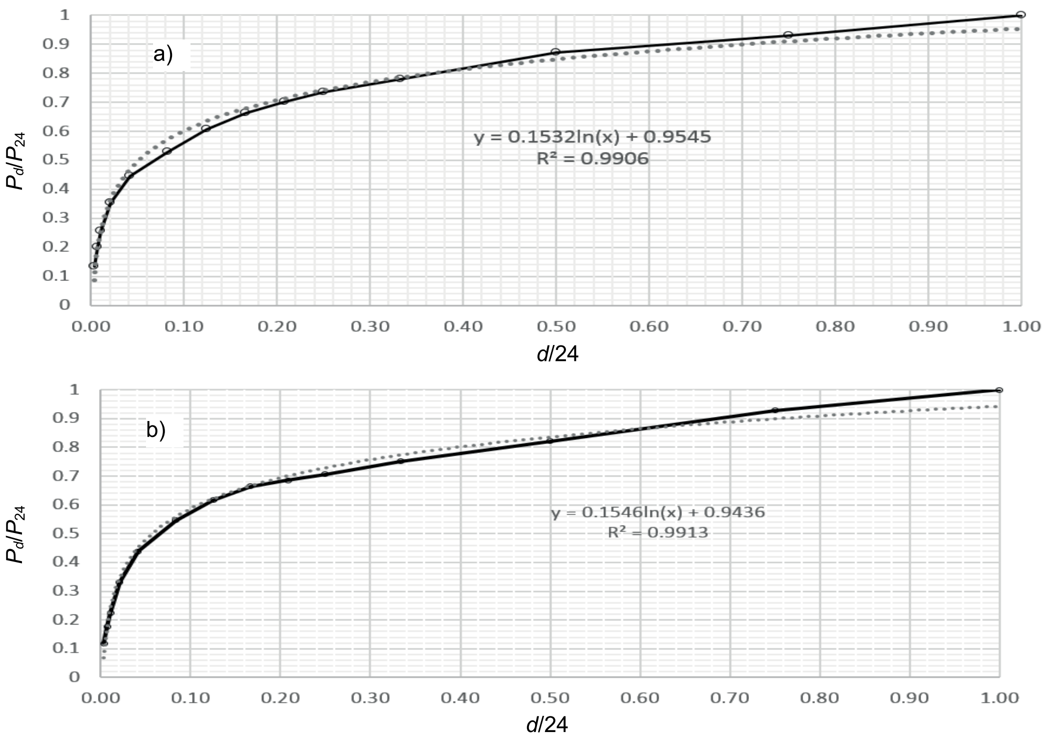

Fig. 2. Standard duration maximum rainfall envelope curves for: a) Malkara station in Marmara Region; b) Giresun station in the Eastern Black Sea Region; source: own study

Table 5. Evaluation indicators for calibration stage

Region	*a*			*b*		
	MRE	*RMSE*	*NSE*	*MRE*	*RMSE*	*NSE*
Marmara	0.023	0.004	0.740	0.025	0.027	0.467
Eastern Black Sea	0.040	0.007	0.687	0.017	0.020	0.652

Explanations: *MRE* = mean relative error, *RMSE* = root mean square error, *NSE* = Nash–Sutcliffe model efficiency.
Source: own study.

Marmara Region, the *SDMR*'s envelope curve was fitted to the logarithmic model, and the regression coefficients were obtained. *MRE*, *RMSE*, and *NSE* values are also given in Table 5.

CONCLUSIONS

Intensity-duration-frequency data, or design rainfall are the significant information required for various hydrological studies, and studies on water resources. However, such necessary data is often not available in various parts of the world due to insufficient gauging stations. It is sometimes impossible to calculate design rainfall due to the lack or deficiency of short-term data. In general, the number of daily gauging stations is more than that of sub-daily gauging stations, and this causes difficulty in obtaining sufficient short-term rainfall values. Therefore, any graphical or mathematical relationship may be useful for rapid estimation of short-term design rainfall from daily data recorded by daily gauging stations

The present study intends to determine sub-daily (short-duration) rainfall using a multiple linear regression model with geographical and meteorological inputs. The approach suggested in this work used the long-term standard duration maximum rainfall records for determining the envelope curve (P_d/P_{24} versus $d/24$). In the first part of the study, the envelope curves of each station were generated. The coefficients (*a, b*) were then obtained from the envelope curves. In the second part, these coefficients were estimated by using multiple linear regression where meteorological and geographical data were included as independent variables. For the coefficient (*a*), the regression predictors were found as the annual total rainfall and the monthly maximum rainfall, whereas for the coefficient (*b*), predictors were determined as latitude, longitude, altitude, and the monthly maximum rainfall.

The suggested model was both calibrated and validated by rain gauge records obtained for the Marmara Region in Turkey. The average coefficient of determination (R^2) for the envelope curves obtained from Marmara Regions was 0.973. In the second step, the meteorological and geographical variables obtained from Marmara Region were used for modelling the coefficients (*a*, *b*). The model's accuracy was found to be satisfactory according to the model metrics such as mean relative error, root mean square error, and Nash-Sutcliffe model efficiency coefficient. For instance, the *MRE*, *RMSE*, and *NSE* values for *a*-coefficient are

0.023, 0.004, and 0.740, respectively, whereas metrics corresponding to the *b*-coefficient are 0.025, 0.027, and 0.467. The model accuracy was further investigated by its application to the Eastern Black Sea Region, Turkey. It is important to mention that the Eastern Black Sea Region has different meteorological conditions and geographical characteristics comparing to the Marmara Region.

The obtained results showed that the model is valid for distinct geographical locations with different meteorological conditions. For instance, the *MRE*, *RMSE*, and *NSE* values for the Eastern Black Sea *a*-coefficient are 0.040, 0.007, and 0.687, respectively. On the other hand, metrics corresponding to the *b*-coefficient are 0.017, 0.020, and 0.652. The results obtained in this study are useful to conduct an accurate estimation of short-duration rainfall. Thus, the planning and design of urban infrastructure will be more efficient. In addition, the model presented in this study will contribute to the estimation of short-duration rainfall in ungauged measurement locations. The model application is not limited and can be conducted for distinct geographical locations.

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