



RESEARCH ARTICLE

ANALYSIS AND COMPARISON OF SPATIAL RAINFALL DISTRIBUTION APPLYING
DIFFERENT INTERPOLATION METHODS IN PORSUK RIVER BASIN, TURKEY

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ABSTRACT

Porsuk River Basin, located in the Central Anatolia, Turkey, has a drainage area of 10818.41 km² and a total length of 460 km, which makes it a significant region for a variety of hydrological and hydropower studies. Therefore, it is necessary to determine the rainfall distribution over the basin so that related projects and processes, such as dam planning works, can be properly performed. To fulfil this aim, the meteorological data gauged between 1927-2015 by 15 different stations within and around the study area were used to perform interpolation functions with three widely known spatial distribution methods, namely Thiessen Polygons (TP), Spline (SP) and Inverse Distance Weighting (IDW), for the determination of the rainfall distribution. Moreover, the reliability of these methods was also evaluated and compared in terms of their Mean Absolute Error (MAE), Mean Square Error (MSE), Root Mean Square Error (RMSE) and Correlation Coefficient (R²) values. The results revealed that IDW method, in general, was the most appropriate option for Porsuk River Basin in comparison with SP and TP methods, as MAE, MSE, RMSE and R² values of this method was found 33.359, 1710.385, 41.357 and 0.7118 respectively. However, TP displayed smoother results at the points where the rain gauges were closer to each other or dense.

Keywords: Rainfall Distribution, Inverse Distance Weighting (IDW), Spline (SP), Thiessen Polygon (TP), Porsuk River Basin

1. INTRODUCTION

Precipitation is one of the foremost variables used to specify the water quantity entering in the hydrologic cycle and regulating water availability [1–3]. Quantitative estimation of precipitation is essential for a variety of fields such as hydrological modelling, water resource management, forecasting of flood and drought, climate research, water balance calculations, irrigation scheduling and hydropower [4–6]. Through all the hydro-meteorological parameters, spatial interpolation of the precipitation is the most challenging and instinctively more difficult, since rainfall is periodic, spatially discontinuous and usually has zero accumulations. Moreover, it is not possible to perform interpolation in all conditions for rainfall [7]. Consequently, a good number of studies demonstrate the rainfall distribution methods and estimations in a wide range of areas. For example, Barros and Lettenmaier [8] focused on the orographic precipitation modelling and remarked that orographic precipitation had high spatial variability in terms of space and time. Nearing et al. [9] studied the future changes in rainfall and their relation with the increase in global soil erosion. Michaelides et al. [3] dealt with the measurement, remote sensing, climatology and modelling of precipitation in their study. In a good number of studies, different interpolation methods such as kriging and inverse distance weighting (IDW) were either utilized or compared for the estimation of rainfall distribution [10–19].

Most of the researchers have underlined that accuracy is of prime importance in the evaluation of precipitation. For this reason, accurate precipitation data have been very important for most of the

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studies dealing with hydrological research. In addition, accurate precipitation data are amongst the paramount factors of climate change, particularly in case a part of water resources is comprised. Consequently, it is very significant to determine the spatial distribution of the rainfall. From this point, using weights from separate precipitation gauges could be proper at small ranges. However, particular interest has to be taken into account to describe the spatial precipitation models properly that are generally interpolated from point scales [20, 21]. Numerous factors affect the accuracy of the interpolation results. These factors vary in a wide range of issues such as density of the samples, quality of the secondary information, and size of the pixels or resolution. Still, the number of steady explanations about the effects of these criteria on the performance of the spatial interpolation applications is inadequate [22].

Within this context, the main purpose of this study is to designate the most proper method of interpolation for the rain gauge network (15 rain gauges) spread in and around the study area, the Porsuk River Basin, which has a drainage area of 10818,41 km² and is located in the northwest of the Central Anatolia, Turkey. There are numerous methods of deterministic/non-geostatistical model in the literature that are put forward by the authors for distributing the precipitation data spatially. Remarkable diligence has been spent for presenting optimum parameters essential for some of the interpolation models. The most prevalently used ones, namely the Thiessen Polygons (TP), Spline (SP) and IDW were utilized in this paper for the estimation of the annual rainfall over the basin, followed by their comparison with each other.

2. DATA AND METHOD

2.1. Definition of the Study Area

The study area is Porsuk River Basin (sub-basin of Sakarya River) positioned in the northwest of Central Anatolia, Turkey, between 38° 44' 00" - 39° 99' 00" east latitudes and 29° 38' 00" - 31° 59' 00" north longitudes. Its length is 202 km and 135 km in the directions of east-west and north-south respectively (Figure 1). Porsuk River Basin covers a drainage area of 10818.41 km², which corresponds to 1.4% of Turkey's surface area. The basin area is also of great significance in terms of natural and cultural characteristics, and therefore has been case study area for a diversity of disciplines [23].

Surface water of the basin is originated from Porsuk River and its sub-streams. The river, rising from Murat Mountains and flowing towards Kutahya province is a tributary of Sakarya River and 460 km in length. After passing from Eskişehir, Kutahya and many other small settlement centres in Turkey, Porsuk River joins to Sakarya River at the station named Sazlılar at an elevation of 660 m. Annual average rainfall depth in Porsuk Basin is approximately 430 mm, corresponding to 481 hm³ volume of water [24–26].

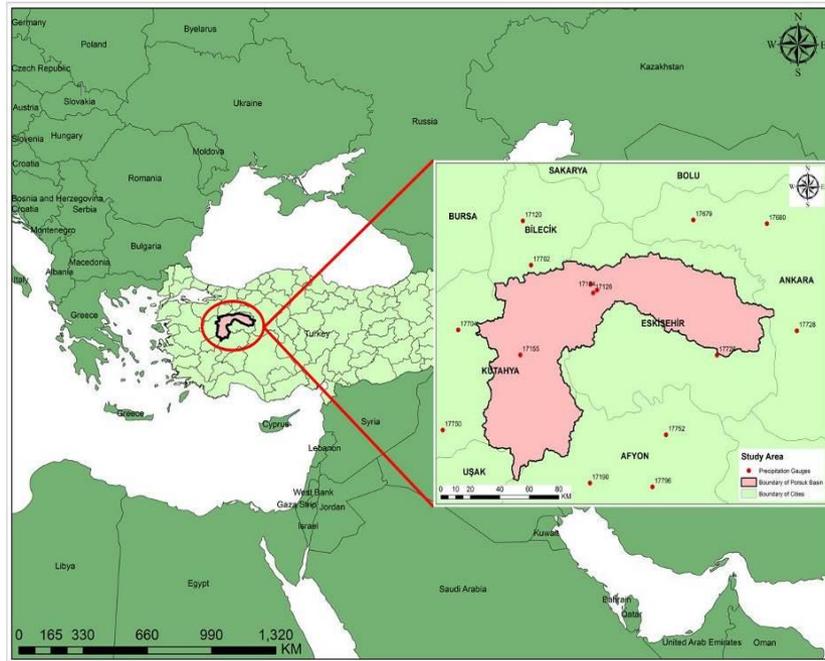


Figure 1. Study area and distribution of precipitation gauges

2.2. Topographic Analyses of Porsuk River Basin

Digital elevation model (DEM) is required to perform a variety of topographic analyses and to produce models for the geological, hydrological, biological and anthropogenic characteristics of the lands [27]. Therefore, DEM was developed in the first place to realize topographic analyses within Porsuk River Basin. To fulfil this aim, 270 1/25000-scale vector maps were obtained from General Directorate of Mapping (GDM), and ArcGIS10 was used for the production of the DEM for the Porsuk River Basin and the surrounding areas. DEM was also used as the major input for the determination of the hydrological basin territories of the study area. Figure 2 illustrates the 1/25.000-scale vector maps and the DEM of Porsuk Basin.

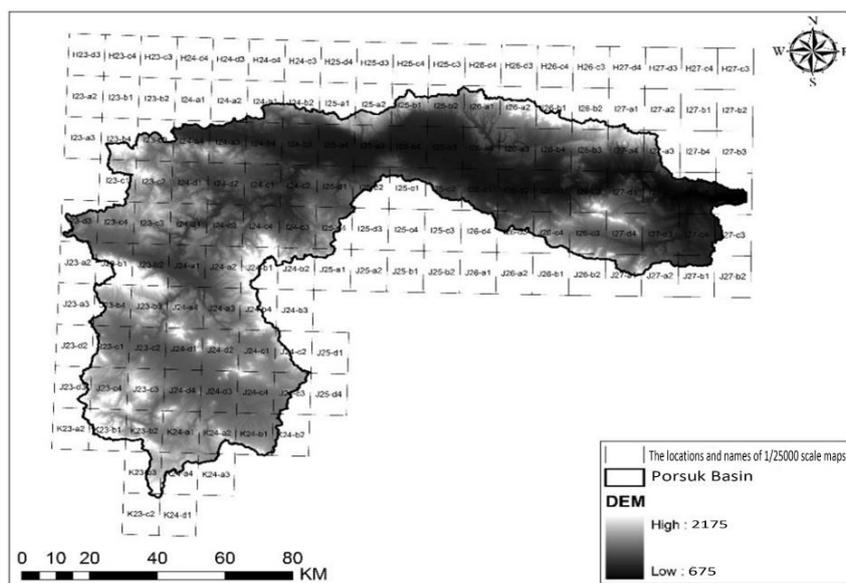


Figure 2. 1/25000-scale vector maps and DEM of Porsuk River Basin

Subsequently, 3D Analyst tool of ArcGIS was utilized for the determination of spatial characteristics of the study area such as elevation, slope, aspect and hillshade, which are also of great importance for the dam planning processes. The spatial characteristics were classified with the geostatistical methods. The illustrations in Figure 3 give the spatial characteristics maps of Porsuk River Basin.

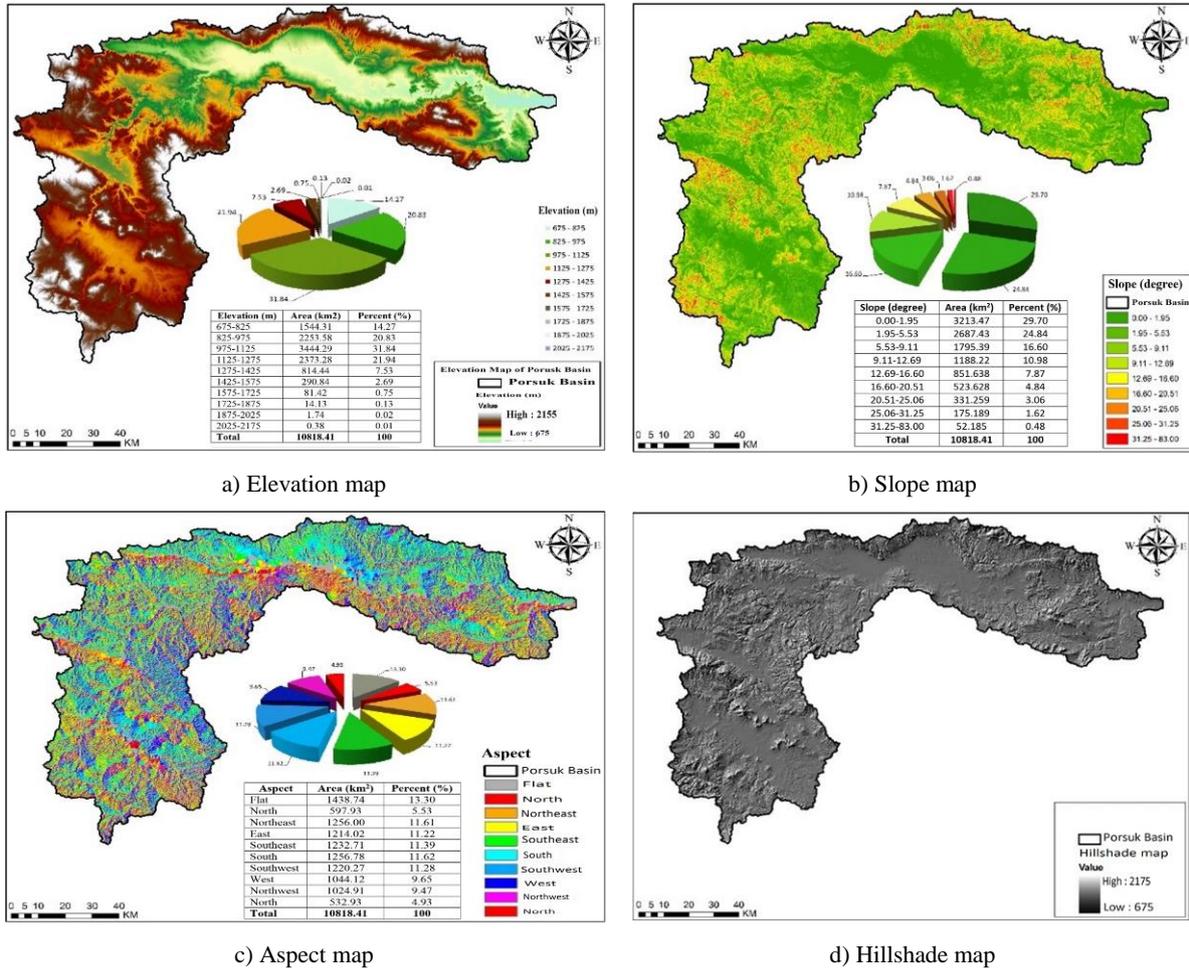


Figure 3. Topographical maps of Porsuk Basin

Elevation Map (Figure 3-a): Counter lines are the major inputs used for producing elevation maps. Counters include the elevation information of the irregular points they comprise. This elevation data is transformed into points having a regular grid format when they are transferred into the digital environment. DEMs are frequently beneficial in hydrological areas, as they provide requisite information necessary for the determination of the elevation differences, slope, direction and drainage network. According to the elevation analysis results, the highest elevation in the basin is located approximately on an altitude of 2175 m, while the lowest elevation is 675 m from the sea level in the Porsuk River Basin. In other words, the elevation in the basin varies between 675-2175 m. The regions between the altitudes of 675-825 m comprise 14,27% (1,544,31 km²) of the total basin area, while the elevations between the ranges of 825 - 975 m, 975 - 1125 m, 1125 - 1275 m and 1275 - 2175 m respectively correspond to 20,83% (2253,58 km²), 31,84% (3444,29 km²), 21,94% (2373,28 km²), and 11,13% (1202,95 km²) of the Porsuk River Basin.

Slope Map (Figure 3-b): Slope basically refers to the ratio of the horizontal and vertical distances between two different locations. It is also explained as the vertical deviation amount in every 100 meters

of horizontal distance. As discharge and drop height are significant factors in the hydrological potential determination studies, the slope of the basin has direct effect on these two factors. The regions in the Porsuk River Basin with the slope degrees of 0.000-9.110 and 9.110-830 respectively cover the 71.14% (7696.29 km²) and 28.86% (3122.12 km²) of the total area. Most of the basin territory is flat. The slopes greater than 31.25⁰ are considerably rare and only comprise 0.48% (52.185 km²) of the basin.

Aspect Map (Figure 3-c): Aspect is the direction of a plane tangent to a point and is represented in degrees. It is measured clockwise starting from north Aspect data can provide information about how the different elevations are influenced by the factors including solar radiation and north winds. According to the map given in Figure 3-c, 22.61% (2446.73 km²) of the Porsuk River Basin has east-southeast faced slopes.

Hillshade Map (Figure 3-d): Hillshade refers to the 3 dimensional topographic map of a land, including the shadow and light areas occurring with regard to a hypothetical source of light. Hillshade maps are produced from DEM data and are useful for visual enhancement. The hillshade map of the Porsuk River Basin helps comprehend the general structure of the basin in terms of topographical characteristics.

2.3. Interpolation Methods

There are numerous methods of deterministic/non-geostatistical model to estimate spatial distribution of precipitation. The most commonly used ones, as they distribute the data in a reasonable separate means, are the TP, IDW and SP. Therefore, these three methods were preferred for the determination of the rainfall distribution in the study area. TP and IDW are based on the quantity of gauged data and its location. The weighted average of the regionalized gauged data is the only parameter taken into consideration to forecast the regionalized quantity. SP is another mathematical method in which different polynomials are fit for each interval between the points. In SP method, a polynomial function passing the representative points is fit to a fixed number of the closest points [28].

Three methods of spatial interpolation discussed above were reviewed in this study. This section gives a brief information about each method.

The following equation gives the calculation formula of the areal rainfall over an area (A):

$$P_t^A = \frac{1}{A} \int_A P_t(x, y) dx dy \quad (1)$$

where $P_t(x, y)$ is precipitation depth at (x, y) point and t^{th} time interval. The total precipitation depth, P_t^A , over A is not known, because finite number of locations n (number of rain gauges) is required for accessing the precipitation depth. A is calculated via the weighted mean of $P_t^1, P_t^2, \dots, P_t^n$ variables of rainfall gauges as in the following formula;

$$P_t^{*A} = \sum_{i=1}^n w_i \times P_t^i \quad (2)$$

where w_i represents the weights of which sum is equal to 1 ($\sum_{i=1}^n w_i = 1$). The three linear estimators we compare, TP, SP, and IDW, differ from one to another in the values of the weights w_i [25, 29].

2.3.1. Thiessen polygons (TP)

TP, also known as Dirichlet tessellations, Voronoi diagrams or Nearest neighbours, is one of the simplest methods of interpolation. The value at an unknown point is based on the observed data of the nearest sample point. In other words, in TP, values at the locations where no gauges were recorded are predicted assuming that these values are equal to that of the nearest gauged data. TP is generally applied for

climatic analyses in local areas where no records exist, and the data of the surrounding weather stations are appropriate for performing the estimations. In TP method, an “influence region” around each point set is designated, in which a particular point within a polygon is accepted closer to a point on the polygon than any other point and thus has the same value [30]. The polygon surfaces are then determined and each of them are used for balancing the amount of the precipitation gauged by the stations that are located at centre of the polygon. In case of a new station inclusion or removal to the system, the polygon is modified [31]. Despite being preferable compared to the approach that uses the average of the stations, it is not possible to utilize TP especially in mountainous regions, since it does not allow for the orographic influence [25, 32]. TP method gives considerably reliable results in areas where the gauge network is dense, and therefore is usually avoided in case the number of the stations is inadequate [33]. In this method, there are n number of influence zones, A_i , which divide the basin area, A . There is one particular A_i for each rain gauge. The points that are closer to a particular station than the others delineate the A_i of a rain gauge. The following formula gives the calculation of the weighting coefficients w_i ;

$$w_i = \frac{A_i}{A} \quad i = 1, 2, \dots, n \quad (3)$$

where $A_i = A/n$.

Eq. 2 is used for estimating areal rainfall (see Eq. 2). When there are missing data at the stations, weights must be calculated again for the remaining stations. This method is very familiar to hydrologists and can provide good estimations with dense networks [25, 29].

2.3.2. Spline (SP)

Basis of SP techniques was first presented by Wahba [34] and numerically developed by Hutchinson [35] for climatic application facts [36]. SP is another mathematical function based method, which minimizes the overall surface curvature, to make estimations for values. The results create a smooth surface using exactly the input data points. Thus, the method, as a concept feature, subtracts the magnitudes of the sample points according to the precipitation heights. Spline bends the elastic surface through the input points while minimizing the total curvature of the surface. As it passes through sample points, it fits a specified number of nearest input points with a mathematical function. This method is preferred because the data changes slowly in parameters such as altitude, water depth and air pollution. [37]. However, if there is a sudden large change in the data at a horizontal distance, the estimation values may move away from the correct results. The method minimizes the function that combines the roughness of the signal surface and the mean square residues. This causes the data to become smooth [38]. In SP, w_i is computed via a co-variance function (see Eq 2), as given in the below formula;

$$C_{(d)} = d^k \log(d) \quad (4)$$

$$k = m - 1$$

where $C(d)$ is co-variance function, d stands for the distance between the observation points, and m is the relative derivative order from the observed points.

There are various researches and studies on this providing more detailed information [25, 35]. Among the types of SP that can be used, the regularized SP uses third and higher order derivatives in mathematical function to improve the analytical properties of the thin sheet SP [39].

2.3.3. Inverse distance weighting (IDW)

IDW is one of the simplest and basic interpolation methods. The method is based on the assumption that the relationship and similarity between two points are proportional to the distance between them. The point value explored in the method will be more similar to the known point values located nearby. With this assumption, points close to unknown points will have more effect (weight) in the calculations. In the IDW method, each sample point has a weight value that is inversely proportional to its distance from the point to be estimated. In other words, in estimating the unknown point, estimation is made by giving much weight to close ones of known points and less to distant ones. In the literature, although there is no definite recommendation for determining the amount of data and exponential coefficient, the most commonly used coefficient is the square of the distance [25, 40]. As it has been also mentioned before, IDW interpolation method differs from TP and SP methods in terms of determining the weights in the mathematical function. In the IDW method, weights are only a function of the distances between the point of interest (x0, y0) and precipitation data (xi, yi). This relationship is given by:

$$w_i = \frac{f(d_{oi})}{\sum_{i=1}^n f(d_{oi})} \quad (5)$$

where d_{oi} is the distance between the point of interest and the i^{th} sample.

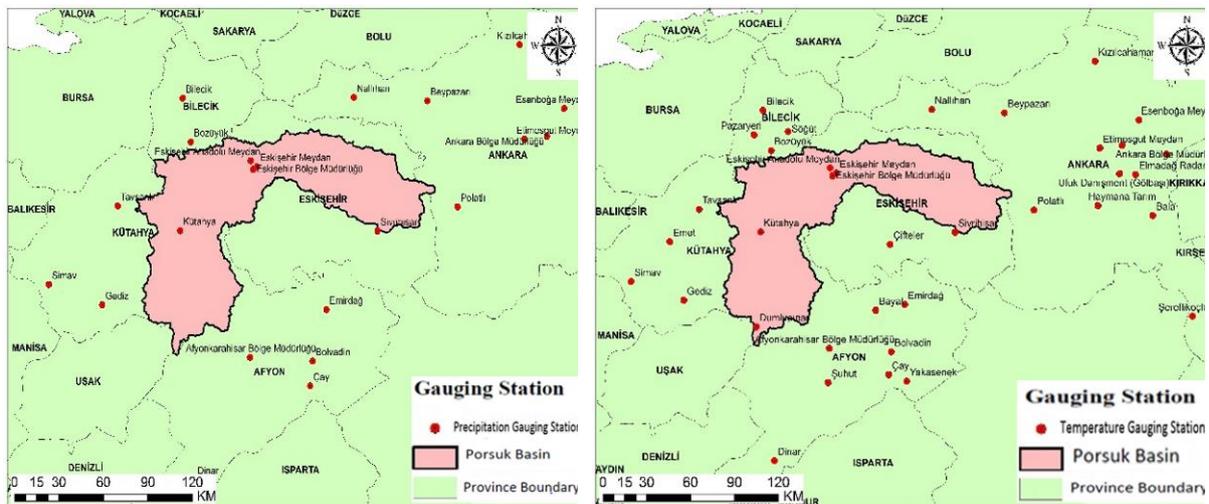
Function $f(d_{oi})$ is a distance function given by:

$$f(d_{oi}) = \frac{1}{d_{oi}^\beta} \quad (6)$$

where β is the power parameter usually from an interval $R(1, 3)$.

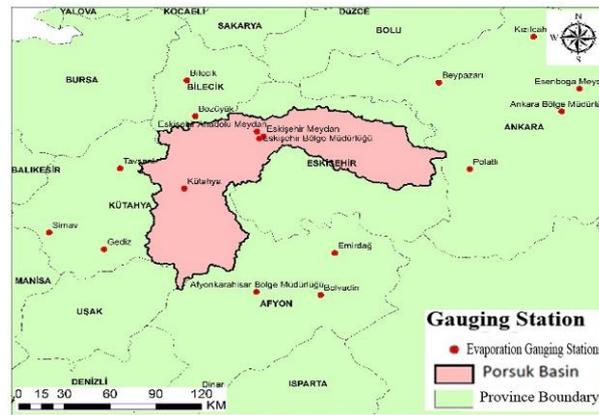
The power parameter reveals the importance of the interpolated values of the spatial data used in spatial estimation. Equation (5) shows that a higher power parameter causes the data at distant points to have less effect on interpolation. The nearby data have a stronger effect. As mentioned earlier, the most common value used as the power parameter is 2.

Figure 4 illustrates the locations of the meteorology gauge stations (MOS), of which precipitation, temperature and evaporation data were used for the determination of the rainfall distribution in the study area with TP, SP and IDW methods.



a) Precipitation gauge stations

b) Temperature gauge stations



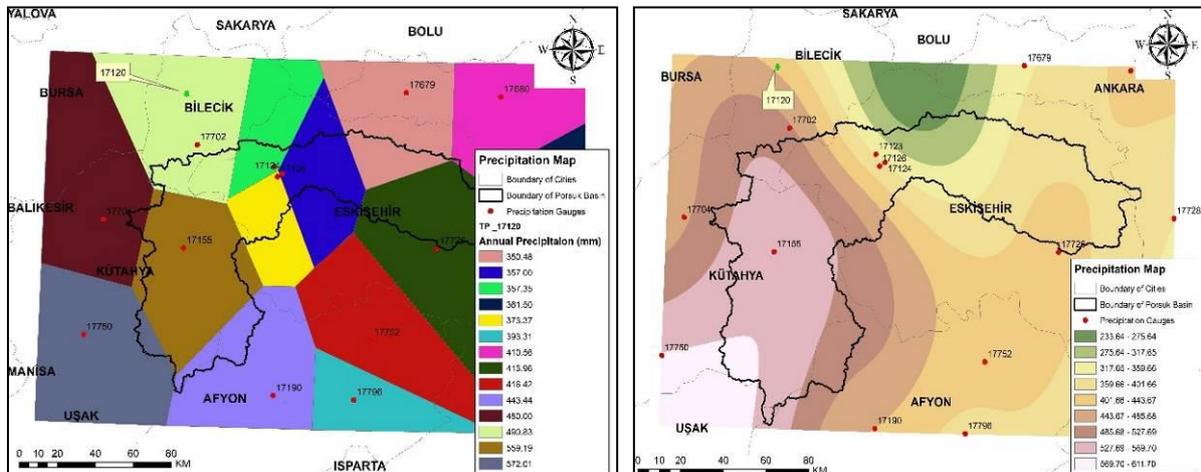
c) Evaporation gauge stations

Figure 4. Locations of the meteorology gauge stations

2.4. Precipitation Data

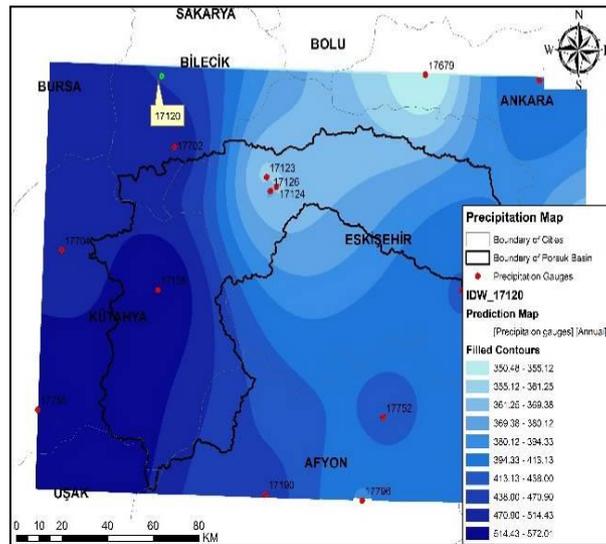
Meteorological factors are of great necessity for the analyses and evaluation of the hydrological resources. It is necessary to analyse the data in the region such as precipitation, temperature, and evaporation during the dam planning processes as well. For this reason, the raw data of precipitation, temperature, and evaporation, which were gauged between 1927-2015 by 15 stations within and around the basin, were obtained from the General Directorate of Meteorological Services [25, 41].

The data were carefully examined and then interpolated using TP, SP and IDW methods via ArcGIS10 capabilities so as to produce the maps given in Figure 5.



a) TP method results

b) SP method results



c) IDW method results

Figure 5. Interpolation of spatial rainfall distribution within Porsuk River Basin using TP, SP and IDW methods [24,40]

After readjustment of the given data records, annual precipitation was calculated. The calculated annual mean precipitation data of the rain gauges were used in the interpolation methods to predict precipitation values at the missing points. The procedure was put into practice for all 15 gauges located in and around the basin, by removing a single gauge record in each process consecutively. Distribution parameters of the precipitation data are given in Table 1. Besides, the relation between the elevation values of the rain gauge stations and the precipitation values were examined to determine the impact of the topography on the mentioned issue. However, no relation was determined between them.

Table 1. Statistical distribution parameters of meteorological data

Parameters	Precipitation (mm)	Temperature (°C)	Evaporation (mm)
Number of Stations	15	36	18
Minimum	350.48	7.76	0.88
Average	428.95	11.35	90.29
Maximum	572.01	13.17	132.60
Standard Deviation	71.13	1.09	26.79
Median	413,96	11.33	96.29
Skewness Coefficient	0.77	-0.81	-1.99
Kurtosis Coefficient	2.54	4.55	8.18

3. RESULTS AND DISCUSSION

Within this study, annual mean precipitation data of more than 80 years, from 1927 to 2015, were used for the estimation of precipitation values at the missing points. The procedure was implemented on all 15 gauges located within and around the Porsuk River Basin, by removing a single gauge record in each process consecutively. TP, SP and IDW methods were applied for the determination of the spatial distribution of the precipitation. In total, 45 precipitation maps (15 for each method) were created. The interpolation methods resulted in some differences in the distribution of the rainfall in the basin. Three representative sample cases (one for each method) from 45 precipitation maps are shown in Figure 5.

The performance of TP, SP and IDW methods were compared quantitatively with each other by computing their Mean Absolute Error (MAE), Mean Square Error (MSE), Root Mean Square Error (RMSE) and Coefficient of Correlation (R^2) (Figure 6). According to this comparison, the estimation

results for the missing points performed with IDW method were the closest ones to the measured data, in comparison with SP and TP. In general, IDW provided the best performance in terms of MAE, MSE, RMSE and R^2 values which were respectively found 33.359, 1710.385, 41.357 and 0.6667. This was followed by the results of the SP in the second place with the MAE, MSE, RMSE and R^2 values of 34.277, 2377.730, 48.762 and 0.6320, while MAE, MSE, RMSE and R^2 values of the TP method were calculated 41.904, 2401.463, 49.005 and 0.5086 respectively (Table 2).

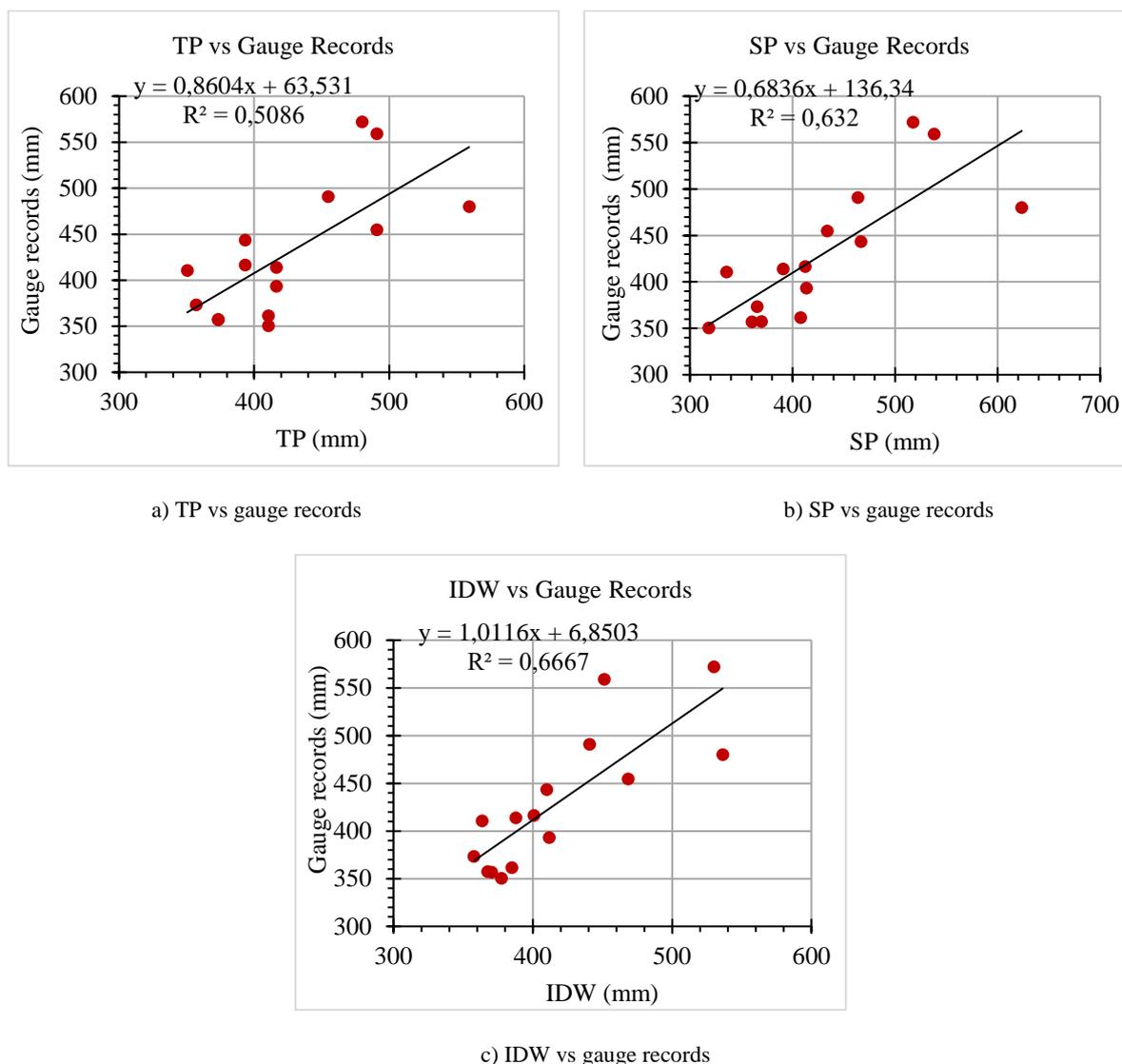


Figure 6. Difference between actual record and predicted values of precipitation with TP, SP and IDW methods [24]

Table 2. Performance measures of IDW, SP and TP methods

RANK	METHOD	MAE	MSE	RMSE	R^2
1.	IDW	33.359	1710.385	41.357	0.6667
2.	SP	34.277	2377.730	48.762	0.6320
3.	TP	41.904	2401.463	49.005	0.5086

As seen in Table 2, the RMSE values increase as the distance between the interpolated stations also increase. On the contrary, the increase in the distance between the interpolated stations results in

decrease in R^2 values. This is assumed to be related with the mathematical basis of the interpolation methods that are based on the distance.

To sum up, the results showed that IDW was the most preferable method and produced a very smooth rainfall distribution when the entire rain gauges were taken into consideration over the basin. However, it was also observed that TP displayed a smoother result at the point where the rain gauges were closer to each other or highly dense. For example, TP had a better result than SP and IDW only at the gauge no 17726. This is because TP method assumes that the value of an unknown point is equal to the amount of the nearest gauged data in that region.

4. CONCLUSION

Displaying remarkable changes across time and space, precipitation is one of the most significant climatic factors for environmental applications. Accurate precipitation data are extremely important for the estimation of surface water, ground water, forecast of events such as floods, draughts and other hydrological studies. Spatial interpolation techniques are commonly utilized for the development of the precipitation distribution models over an area. Nevertheless, the rain gauge network in target areas is not always dense enough to perform accurate analyses and projections, and therefore a diversity of spatial interpolation methods is applied to overcome the shortcomings. Yet, utilization of such different interpolation methods may end up with different results that are not always accurate enough compared to the actual spatial distribution of precipitation. In this study, three different interpolation methods of non-geostatistical model were investigated with regard to their suitability to spatially distribute the precipitation in the Porsuk River Basin, located in the northwest of Central Anatolia, Turkey.

The results of these three interpolation methods were also compared within the context of the study. The accuracy of interpolation methods was determined by using the MAE, MSE, RMSE and R^2 as the validation criteria. The sample interpolation results for each method were given in Figure 5. However, it is necessary to remark that none of the methods are significantly superior to the other. In IDW method, the most commonly used power parameter is 2. Moreover, the default power parameter in ArcGIS program is also 2. In this study, it was observed that the best deterministic interpolation scheme was IDW, with a squared power parameter ($\beta = 2$). SP ranked in the second place and TP was determined as the least efficient method, since TP validation results concluded the highest MAE, MSE, RMSE and a minimum of R^2 values.

It is still suggested that a number of different interpolation methods and other common schemes, as well as their combinations should also be practiced to obtain an optimal value with the best performance in the Porsuk River Basin, since the three employed methods in this study may not be sufficient to get the most accurate and precise distribution results. Moreover, in future studies, different power parameters should also be used to perform more comprehensive accuracy analyses for the IDW method. This way, the most optimum power parameter can be determined to obtain results with minimum standard errors.

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