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Critique and spatialization of mean rainfall in the Oued Lakhdar watershed upstream of the Hassan I dam: use of interpolation methods (deterministic, probabilistic) integrated into GIS

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Abstract: Rainfall data are important for hydrometeorological studies and catchment management. Still, we looked for alternative and efficient methods to cover the entire study area due to the rugged terrain of the Oued Lakhdar catchment, which has only three inland stations. The main objective of this study is to show the importance of GIS in selecting the optimal mean rainfall map using different methods. Firstly, we assessed data reliability from the Agence du Bassin Hydraulique de l'Oum Er Rbia (ABHOR). Secondly, we explored the three deterministic methods (IDW, RBF, and LPI) as well as the three geostatistical methods (OK, UK, and EBK) to select the optimal method for spatializing mean precipitation over the period 1985-2021 in the Oued Lakhdar watershed. The choice of method was based on a comparison of statistical parameters such as RMSE, ME, and R2. We compared the interpolated values obtained with the values measured in the field, revealing that universal kriging proved to be the optimum method with (RMSE = 41.71; ME= 7.09 and R2 = 83%). So, we can use the results of this study to manage water and soil resources, as most studies call for using the spatialized precipitation map as one of the factors in the issues at stake.

1. Introduction

Estimating average rainfall in the watershed is very important in many hydrological studies for natural resource management and hydrological modeling (Bayat *et al.*, 2012; Ly *et al.*, 2011). In other words, knowledge of the spatial and geographical distribution of rainfall in a watershed requires a very dense network of rain gauges to manage the water resource in that watershed, which entails very high installation and operating costs (Eldrandaly and Abu-Zaid 2011). We chose interpolation methods integrating GIS to estimate precipitation in unsampled locations due to the insufficiency of localized stations within this basin (Li and Heap, 2008; Longley *et al.*, 2011). There are several methods for calculating average rainfall from the set of point measurements obtained at several rain gauge stations on or near the basin. Spatial interpolation methods can be categorized into two groups (Layati *et al.*, 2020; Layati and El Ghachi, 2021; Bhunia *et al.*, 2018):

- ✓ Deterministic methods, LPI: Local Polynomial Interpolation, RBF: Radial Basis Functions and IDW: Inverse Distance Weighting;
- ✓ Geostatistical methods, EBK: Empirical Bayesian Kriging and Kriging (UK and OK);

This study aims to criticize and spatialize average rainfall in the Oued Lakhdar watershed by integrating differences between deterministic and probabilistic interpolations in the ArcGIS 10.4.1 geographic information system.

2. Materials and methods

2.1 Site Description

The study area chosen to apply interpolation and spatialization of mean annual rainfall, using two methods: geostatistical and deterministic, in the Oued Lakhdar watershed (Beni Mellal-Khenifra Region, Morocco). This basin lies between latitude 31°57′20″ and 31°28′55″ north, and longitude 6°49′49″ and 6°08′18″ west (Layati *et al*., 2022). This basin covers most of the mountainous area of the Azilal region, with a total surface area of around 1638 km². **Figure 1** shows the location of stations both inside and outside the basin (**Figure 1** and **Table 1**). In the Oued Lakhdar watershed, there are only three inland rainfall stations (Addamaghne, Sgat, and Barrage Hassan I), which leads us to look for outside stations to help with spatialization (Bge Moulay Youssef, Bge Sidi Driss, Ait Segmine, Assaka, Zaouit Ahnsal, Tilouguit, Tamesmat, and Ait Tamlil).

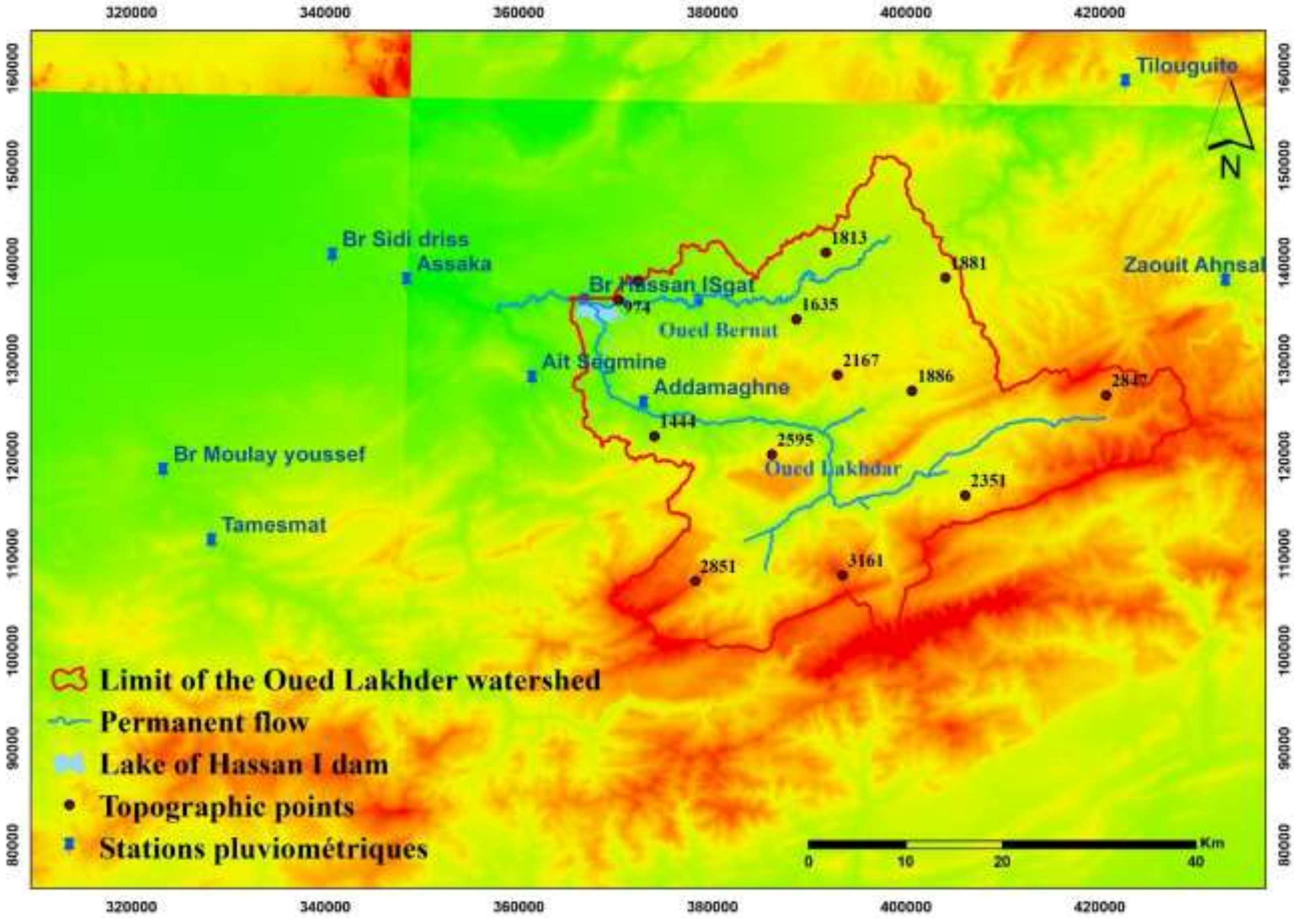


Figure 1. Location of stations outside and inside the basin

Table 1. Location and chronicle of rainfall stations selected by ABHOR

Stations	Lambert coordinates			Chronicle	Type of station	Inside or outside	Source
	x	y	z				
Sgat	377800	136100	1150	1985-2021	Rain gauge stations	Inside	ABHOR
Addamaghne	372900	125400	1125			Inside	
Bge Hassan I	365500	137300	825			Inside	
Bge Moulay youssef	323300	118500	880			Outside	
Bge Sidi driss	340800	140600	640			Outside	
Ait Segmine	361400	128000	1025			Outside	
Assaka	348450	138100	684			Outside	
Zaouit Ahnsal	433016	137983	1595			Outside	
Tilouguit	422670	158500	1100			Outside	
Tamesmat	328300	111200	920			Outside	
Ait Tamlil	357600	93700	1860			Outside	

2.2 Methodology adopted

- **Critique and homogenization of hydro-climatic data and filling of gaps**

The study of hydrology and climate requires the use of reliable and homogeneous data for accurate and meaningful analyses. However, hydroclimatic data collected from climatological and hydrological stations may contain errors and gaps, which can affect the quality and reliability of the results obtained. For this reason, criticizing and homogenizing hydro-climatic data have become important steps in scientific research in hydrology and climatology. Several studies have been carried out on the criticism and homogenization of hydro-climatic data, including that by El Ghachi (2007) and Lahlou (2021), who examined the homogeneity of precipitation data in the basin using a method based on the correlation between stations. Another study by Cherrad (1997); Qadem (2020) and Qadem (2015) proposed a correction method using simple and double cumulation methods.

In this section, we focus on critiquing and homogenizing hydroclimatic data in the Oued Lakhdar watershed and on filling data gaps. We use a method of simple and double cumulation to ensure homogeneity. We also propose a method for filling data gaps based on the correlation between stations.

- **Filling the gaps**

Some weather monitoring stations have gaps and missing data in their rainfall measurements, which are noticeable during certain months and years. These problems are due to various factors, including:

- Temporary interruptions to monitoring or the absence of the observer, and handling errors;
- Breakdowns or failures of meteorological monitoring equipment (instruments), preventing their operation before replacement;

- Documents and monitoring records damaged or lost during transfer to documentation centers;

We used the linear correlation method (Sirtou, 2018; Ghadbane, 2022), based on the following equation (equation 1), to estimate missing data at the rainfall stations. In other words, this method allows us to estimate missing values based on available data. To obtain more accurate estimates, it is important to take into account the proximity of the measuring stations and to ensure that they belong to the same climatic region:

$$Y = aX + b \quad (1)$$

Where: **Y**, which corresponds to the missing rainfall for a rain gauge station, will be estimated from the variable **X**, representing the available rainfall, where ***a***, is the slope of the straight line.

- **Interpolation and spatialization of rainfall in the Oued Lakhdar watershed**

The selection of interpolation and spatialization methods in this research was based on the popularity of previous hydrological studies (El Ghachi, 2007; Qadem, 2015; Bhunia et *al*., 2018; Lahlou, 2021; Layati et *al*., 2021; El Orfi, 2023). Deterministic methods, such as IDW, RBF, and LPI, as well as probabilistic methods, such as kriging (UK and OK) and EBK, were chosen for the spatialization of mean precipitation in the Oued Lakhdar watershed.

Deterministic interpolation methods

- **IDW method**

The IDW method determines and estimates the interpolated value based on averages weighted by the inverse of the distance between unsampled and sampled points (Johnston et *al*., 2001; Watson and Phillip, 1987; Khouni et al., 2021). It considers that the values of nearby points have a greater influence on the interpolated values than distant observations (Chin et *al*., 2023), i.e., nearby points have more weight. Equation (2) has been used to determine the IDW:

$$Z_0 = \frac{\sum_{i=1}^{N} z_i . d_i^{-n}}{\sum_{i=1}^{N} d_i^{-n}} \quad (2)$$

Where: $\mathbf{Z_0}$= Estimated value at the unsampled station; $\mathbf{d_i}$ = Distance between the unsampled station and the measured station; **n** = Weighting power; $\mathbf{z_i}$ = Observed value; **N** = Number of measured stations in the vicinity;

- **LPI method**

Local polynomial interpolation (LP) is an interpolation method that locally adjusts polynomials to estimate values between discrete data points. This method is often used in geomatics software to create continuous surfaces from scattered data points. In LP, a polynomial is fitted to a set of neighboring points around the interpolation point, and the estimate of the interpolated value is based on this fitted polynomial. Several degrees of polynomials can be used in this method, depending on the complexity of the data variations in the interpolation region, thus minimizing errors in that particular region (Sadeghi et *al*., 2017; Johnston et *al*., 2001; Xiao et al. 2016; Chin et *al*., 2023). Equations (3) and (4) have been used to determine the LPI:

$$w_i = (1 - \frac{d_i}{R})^p \quad (3)$$

$$\sum_{i=1}^{n} w_i (f(x_i , y_i) - z_i)^2 \quad (4)$$

With: d_i: Distance between the grid point (xi, yi) and a data point (x, y); R: Radius of moving circle; p: is a parameter that controls the decrease in weight as a function of distance; n: represents the total number of data points; w_i: is the weight associated with the i-th data point; $f(x_i, y_i)$: is the interpolated value at point (x_i, y_i); z_i: is the actual data value at point (x_i, y_i).

- **RBF method**

The radial basis function (RBF) method relies increasingly on the distance between the independent variable and a reference vector. RBF methods encompass a diverse array of precise interpolation techniques that utilize a fundamental equation based on the spatial separation between the interpolated point and the sample points (Agnieszka and Antoni, 2014). This approach encompasses five distinct basis functions, as identified by Dorffer (2017): cubic spline, thin plate spline, exponential basis, inverse multiquadratic function, and multiquadratic function. The mathematical expression for the RBF method is depicted by the following equation 5 (Njeban, 2018):

$$\emptyset(r) = \sqrt{r^2 + C^2} \qquad \textbf{(5)}$$

Where: **c** is the smoothing factor, and **r** is the distance between the sample and the estimate.

Geostatistical interpolation methods

- **Kriging**

Krige (1951) laid the foundations of kriging, a method for estimating unknown values between known data points. Subsequently, in 1962, French mathematician and geologist Georges Matheron (1962) further developed and formalized this method. Kriging, being a linear, unbiased technique, is used to predict unexplored values in a data set. The assessment of correlations between interpolated and measured values is based on variogram or semivariogram analysis. Three primary forms of kriging exist: universal kriging, ordinary kriging, and simple kriging (Holdaway, 1996).

a) OK method

In the 1980s, Burgess and Webster (1980) were among the first to adopt the OK method to map spatial variances in soil characteristics and gradually outline soil parcels. Ordinary Kriging (OK), which stands for Ordinary Kriging, is employed to compute the unbiased linear estimation of a stationary random field defined by an unknown constant mean (Burgess and Webster, 1980; Amoroso et *al*., 2023). The OK is calculated by the following equation (Equation 6):

$$Z^*(x_0) = \sum_{i=1}^{n} \gamma_i Z(x_i) \qquad \textbf{(6)}$$

Where: $\mathbf{Z^*(x_0)}$: This is the estimated value of the geographic phenomenon at location $\mathbf{x_0}$; $\mathbf{Z(x_i)}$: These are the observed values of the geographic phenomenon at known locations $\mathbf{x_i}$ (where i=1,2,...,n).; $\boldsymbol{\gamma_i}$: These are the weights assigned to each observed value of $\mathbf{Z(x_i)}$; The weights $\boldsymbol{\gamma_i}$ are determined as a function of the distance and spatial correlation structure between the data points.

b) UK method

This kriging process is based on the idea that the random function (x) loses its stationarity and its mathematical expectation varies spatially (drifts), reflecting a systematic trend in the distribution of values across space (Wu et *al*., 2019). It is assumed that:

$$Z(x) = m(x) + \in (x) \quad (7)$$

Where: $E(\in (x)) = 0, V(\in (x)) = \sigma^2$ *and* $E(Z(x)) = m(x)$

The trend can be expressed as follows: $$m(x) = \sum_{i=1}^{k} \alpha_i f_i(x) \quad (8)$$

Where: **K** is the number of functions used to model the drift; $\mathbf{f_i}$: is the spatial coordinate basis function describing the drift $\boldsymbol{\alpha_i}$: is the coefficient to be estimated from the data;

- **EBK method**

EBK differs from other classical kriging methods in that the parameters are automatically optimized using a number of semi-variogram models instead of a single semi-variogram (Farina et *al.*, 2017; Bhunia et *al.*, 2018; Sahu et *al.*, 2021; Yang and Xing, 2021), i.e., they are simulated several times and the results of the variogram models are calculated based on the simulated values.

- **Evaluation criteria for interpolators: Cross-validation and comparison of methods**

The comparison of predictions from the different interpolators was carried out by evaluating different measures of prediction error on the points of origin. The RMSE, calculated by equation (9), the coefficient of determination (R^2) obtained from equation (10), and the mean error (ME), also determined by equation (11), were used in this evaluation to select the most appropriate method for spatializing mean annual precipitation in the catchment (Adhikary and Dash, 2017; Taghizadeh et *al.*, 2008; Njeban, 2018; Njoku et *al.*, 2023).

- **Root Mean Square Error (RMSE):** Calculating the **RMSE** indicates how close a model's predictions are to the actual values. In other words, it calculates the mean square error between observed and predicted values. The model's ability to predict real data increases in proportion to its low RMSE. It is calculated using the following formula (equation 9):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(C_0 - C_p)^2}{N}} \quad (9)$$

Where: $\mathbf{C_o}$ is the observed value; $\mathbf{C_p}$ is the predicted value and **N** is the number of values used for estimation.

- **Coefficient of determination (R^2):** Evaluates the agreement between actual observed values and those predicted. This coefficient is generally between 0 and 1. The formula for the R2 is as follows: (equation 10) :

$$R^2 = \frac{\left[\sum_{i=1}^{n}(P_1 - P_{ave})(Q_1 - Q_{ave})\right]^2}{\sum_{i=1}^{n}(P_1 - P_{ave})^2 \sum_{i=1}^{n}(Q_1 - Q_{ave})^2} \quad (10)$$

Where: $\mathbf{P_{ave}}$ is the mean of predicted values; $\mathbf{Q_{ave}}$ is the mean of measured values; **n** is the number of samples used for prediction (Khouni et *al.*, 2021).

- **Mean error (ME)** is utilized for evaluating the degree of bias in estimates, and should ideally be close to zero. High values of mean error indicate significant deviations between predicted and observed values. The ME formula is calculated as follows: (equation 11):

$$ME = \frac{\sum_{i=1}^{n}(C_0 - C_p)^2}{N} \qquad (11)$$

3. Results and Discussion

3.1 Critique and homogenization of hydro-climatic data and filling of gaps

- **Filling gaps**

We have established a matrix of correlation coefficients between stations measuring monthly precipitation by pairing them up. These data are detailed in **Table 2**. According to El Ghachi (2007) and Qadem (2015), the coefficient R^2 is used to assess the quality of a correlation, while the equation of the correlation line is used to compensate for any shortcomings (**Table 3**). R^2 is considered acceptable and good when it is greater than 70%.

Table 2. Correlation matrix between rainfall stations in the Oued Lakhdar watershed between (1985-2021)

	Rain gauge stations										
	Sgat	Addamaghne	Ait Segmine	Aitamlil	Assaka	Barrage Hassan I	Barrage Sidi Dris	Barrage My Youssef	Tilouguite	Zaouit Ahnsal	Tamesmate
Tamesmate	99.88	99.96	99.81	99.67	99.93	99.94	99.9	99.95	99.94	99.96	100
Zaouit ahnsal	99.8	99.94	99.72	99.61	99.86	99.81	99.81	99.9	99.96	100	
Tilouguite	99.79	99.92	99.7	99.45	99.8	99.87	99.79	99.86	100		
Barrage My Youssef	99.91	99.96	99.79	99.82	99.97	99.9	99.96	100			
Barrage Sidi Dris	99.96	99.93	99.86	99.81	99.94	99.92	100				
Barrage Hassan I	99.94	99.94	99.92	99.67	99.87	100					
Assaka	99.87	99.91	99.77	99.83	100						
Aitamlil	99.76	99.74	99.62	100							
Ait Segmine	99.9	99.84	100								
Addamaghne	99.94	100									
Sgat	100										

Table 3 gives an overview of the number of missing months and years in the watershed's rainfall data series, as well as their correlation coefficients.

Table 3. Stations with known monthly and annual rainfall gaps

Stations	Missing periods	Correlated station	R^2(%)
	Years (Month)		
Sgat	**2018** (2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12); **2019**; 2020 (1, 2, 3, 4, 5, 6, 7, 8)	Addamaghne	99.94
Addamaghne	**2018** (3, 4, 5, 6, 7, 8, 9, 10, 11, 12)	Assaka	99.91
Assaka	**1986** (1, 2, 3, 4, 9, 10, 11, 12); 1988; 1989 (1)	Addamaghne	99.91
Ait Segmine	**2019** (2, 3, 4, 5, 6, 9, 10, 11, 12)	Assaka	99.77
Barrage Hassan I	**1983** (4, 9, 10)	Ait Segmine	99.92

3.2 Data homogenization test using simple and double cumulation methods

To assess the homogeneity of hydro-climatic data, statistical methods such as single and double totals are used.

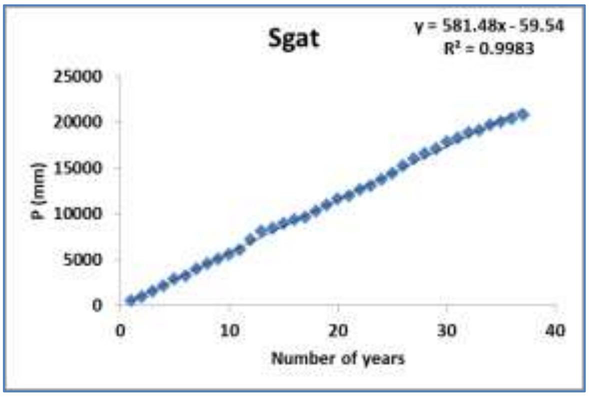
- **Simple accumulation method**

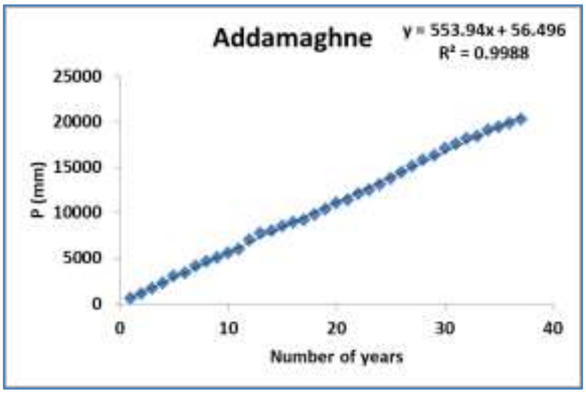
This is a simple statistical method involving the calculation of cumulative annual precipitation quantities from one year to the next (Dubreuil, 1974). This series is represented in the form of a curve, and precipitation measurements are considered homogeneous if the curve is straight or almost straight. If this is not the case, the measurements are not homogeneous.

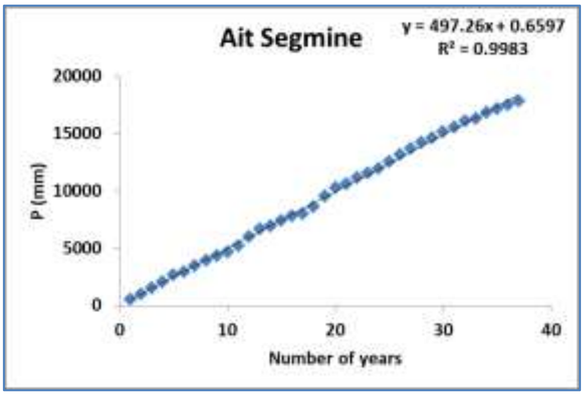
Rainfall data

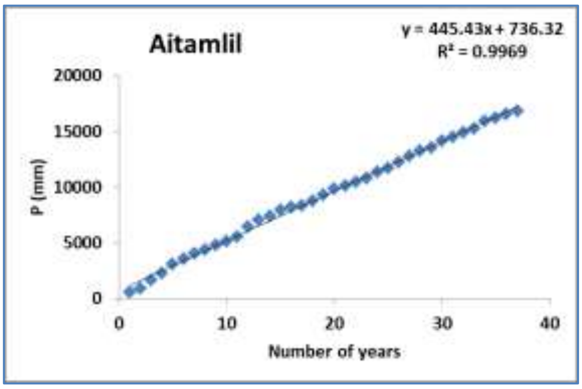
After applying the simple accumulation method to eleven stations, the results obtained were deemed satisfactory. The R^2 correlation coefficients revealed a strong correlation between the data, confirming their validity.

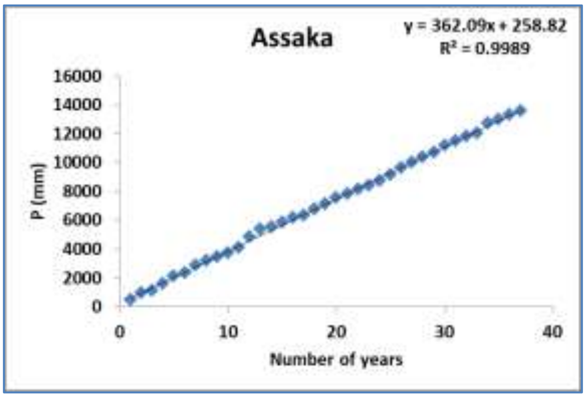
The application of this method gives the following:

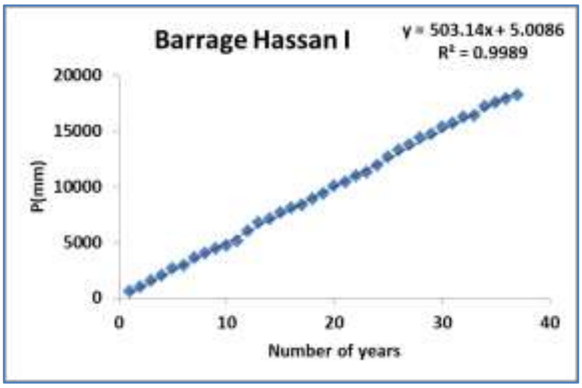












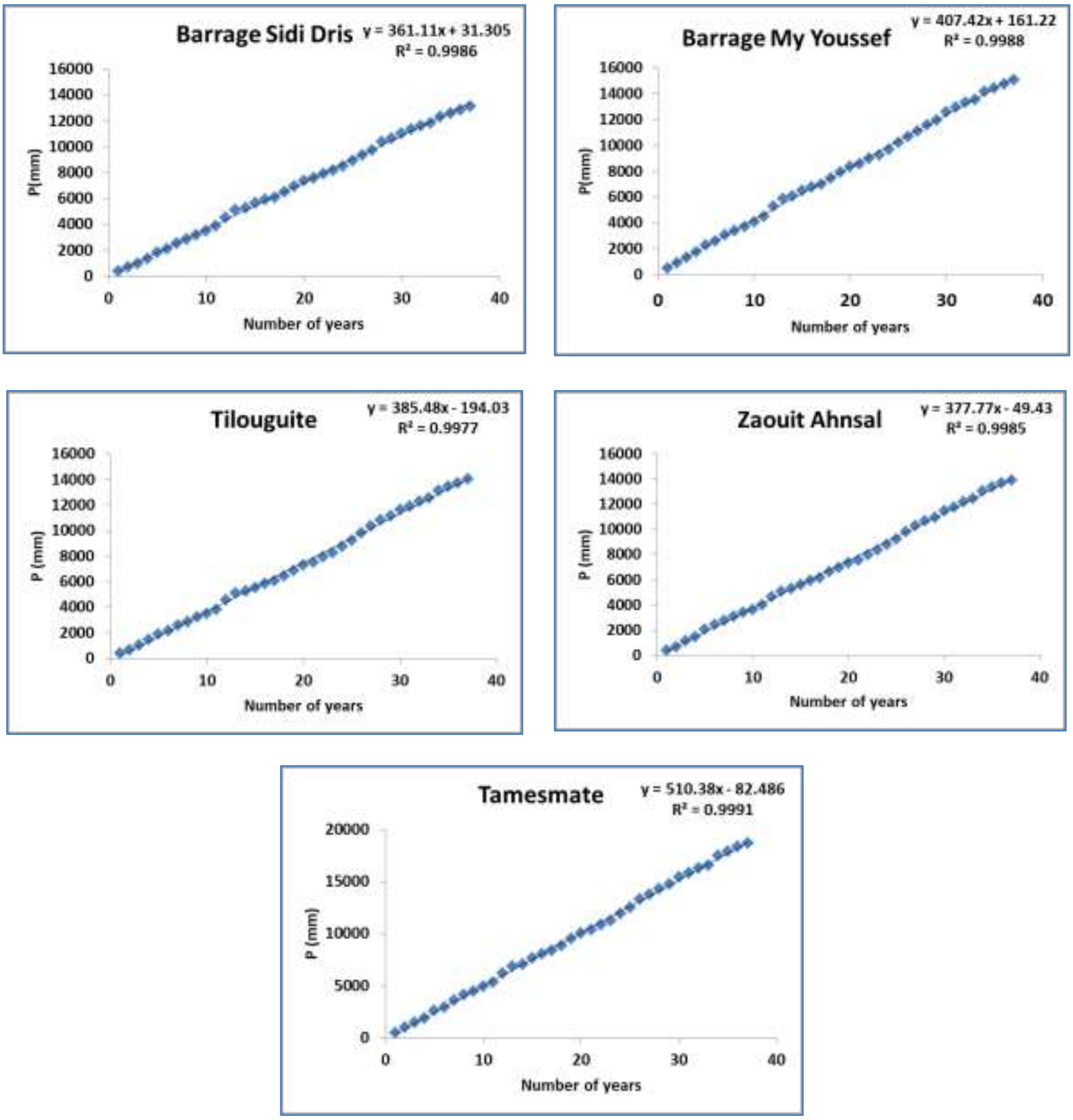


Figure 2. Simple accumulation method for rain gauge stations

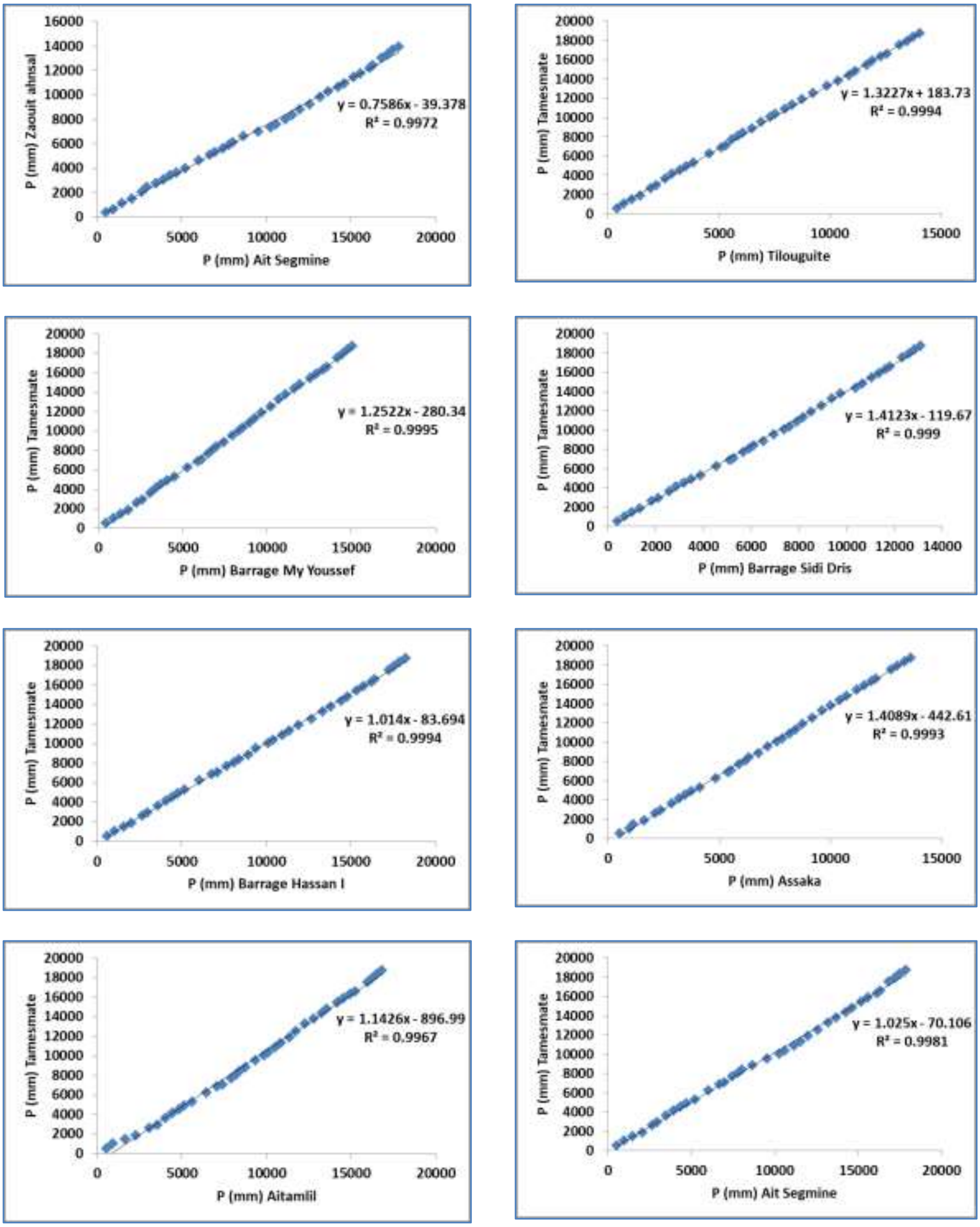
The graphs of the simple rainfall station accumulation method show the cumulative annual rainfall contributions recorded at eleven stations to be monitored as a function of the number of years. The R^2 values for each station are high (**Figure 2**), indicating a strong correlation between the data recorded by each station. This suggests that the data series from the stations tested are fairly homogeneous, so the results obtained are good and satisfactory, as all stations have an R^2 exceeding 80% (Layati and El Ghachi, 2021).

- **Double accumulation method**

This method consists of checking the proportionality of values measured at two stations: one is the base or reference station (station X), which is considered correct, while the other station (station Y) is the station to be checked (Sebbar, 2013).

Rainfall data

Figure 3 shows the results obtained: Out of 55 correlations, they have a coefficient of determination of over 80% (**Table 2** and **Figure 3**), underlining the homogeneity of the data from these stations.



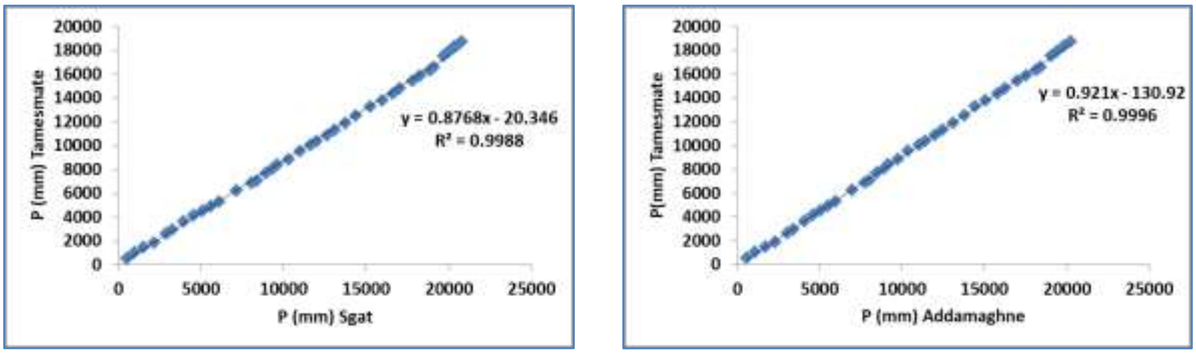


Figure 3. Double accumulation test for rainfall stations

3.3 Interpolation and spatialization of precipitation in the Oued Lakhdar watershed

The six interpolation methods selected were applied to the 11 rainfall stations in the hydrographic network, located both outside and inside the Oued Lakhdar watershed. Three empirical deterministic methods were selected (IDW, LPI, and RBF). In addition, three geostatistical stochastic methods were used (OK, UK, and BEK), and the three statistical parameters were also calculated: RMSE, ME, and R2. The values of these parameters are used to establish the interpolation method best suited to the study area.

- **Exploratory data analysis**

Before initiating a geostatistical analysis, it is essential to conduct an exploratory examination of the data. This preliminary analysis holds significant importance in identifying potential inconsistencies in the assumptions underlying the geostatistical model (Thomas, 2003). Assessing the statistical parameters of spatial interpolation yields valuable insights into the distribution pattern of the variable under examination. For instance, with a kurtosis coefficient of 1.5737, falling below 3, the distribution qualifies as platykurtic, indicating lower kurtosis compared to a normal distribution (**Figure 4**). Additionally, the skewness coefficient (Skewness) of 0.16409, exceeding 0, signifies rightward asymmetry, as discussed in various scholarly works (Layati et *al*., 2020; Zhiqiang et *al*., 2008).

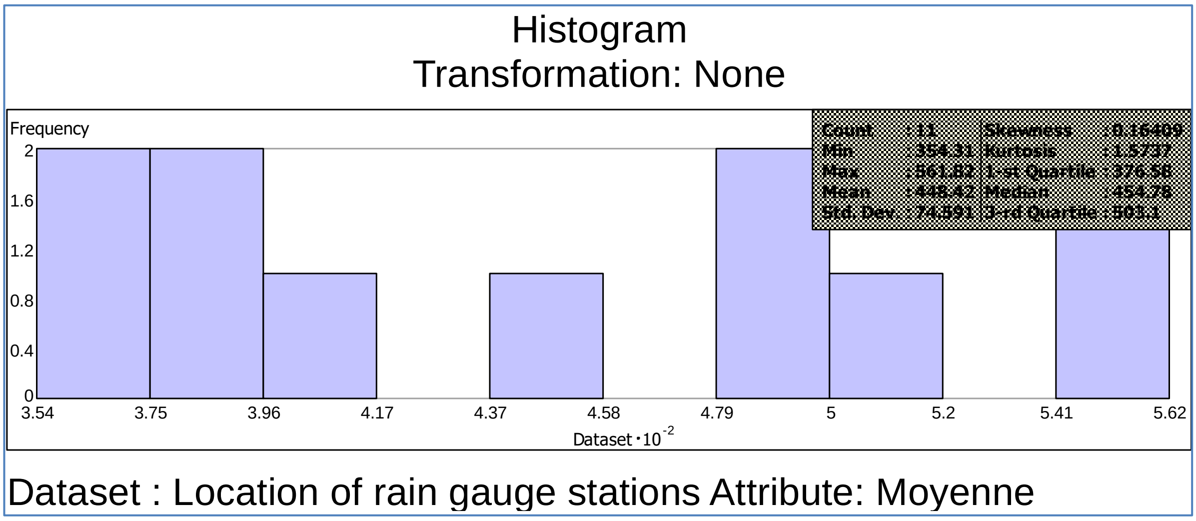


Figure 4. Descriptive statistics for rainfall distribution

- **Cross-validation comparison**

A quantitative evaluation of these three statistical parameters was carried out by cross-validation statistic comparison (**Table 4**). The best model selection was based on three main performance criteria:

the RMSE would be ideally reduced, the ME value would be as close to zero as possible, and the R^2 coefficient of determination would be maximized (Bhunia et *al*., 2018; Agnieszka and Antoni, 2014; Adhikary and Dash, 2014). The results of the cross-validation calculations are displayed in **Table 4**.

Table 4. Error statistics for spatial interpolation methods for rainfall over the observation period (1985-2021)

	Methods					
Prediction errors	**Deterministic / empirical**			**Stochastic probabilistic**		
Interpolation mode	IDW	RBF	LPI	OK	UK	EBK
ME	8.72	7.96	23.96	8.59	7.09	7.70
RMSE	54.15	46.39	83.27	52.17	41.71	45.70
R2	68	73	54	72	83	76

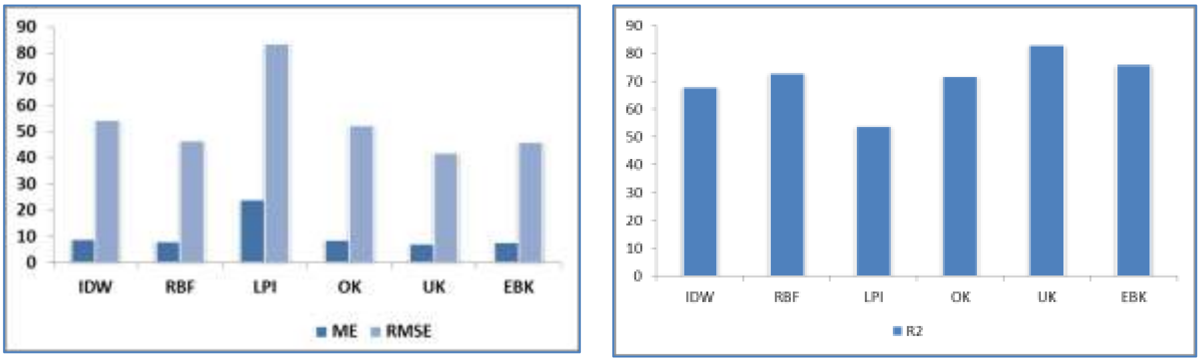


Figure 5. Summary of the different precision performance indicators ME, R^2 and RMSE for each optimization method model.

Among the deterministic methods (**Figure 5** and **Figure 6**), the RBF (Radial Basis Function) method stands out with the lowest RMSE (=46.39), indicating notable accuracy in predictions. The R^2 value is the highest (=76%), and ME has a value of 7.96, which is close to 0. In contrast, the LPI (Local Polynomial Interpolation) method has a higher mean error further from 0 (=23.96), with an RMSE (=83.27), reflecting lower accuracy (R^2 = 54). In terms of stochastic probabilistic methods (**Figure 5** and **Figure 7**), the UK method stands out with the lowest RMSE (=41.71), suggesting superior accuracy compared to other probabilistic methods. The OK method also comes out on top, with the highest coefficient of determination R^2 (83%) of all the methods evaluated.

In terms of efficiency for simulating mean rainfall, the optimal method turns out to be Universal Kriging (UK), generating significant results such as RMSE = 41.71, ME = 7.09 and R^2 = 83%, which confirms several results from other authors (Eldrandaly and Abu-Zaid, 2011; Francisco, 2010; Layati and El Ghachil, 2021) [3, 7, 44]. Analyzing the parameters of the error statistics, we observe a hierarchy among the interpolation methods: RMSE follows the order UK < EBK < RBK < OK < IDW < LPI; mean error follows the order UK < EBK < RBK < OK < IDW < LPI; and R^2 follows the order UK > EBK > RBK > OK > IDW > LPI. These results highlight that the Local Polynomial Interpolation (LPI) method is the least suitable model, suggesting its inapplicability for the spatialization of precipitation in the study area. This analysis underlines the crucial importance of choosing the appropriate interpolation method according to the specific accuracy criteria sought for a particular study.

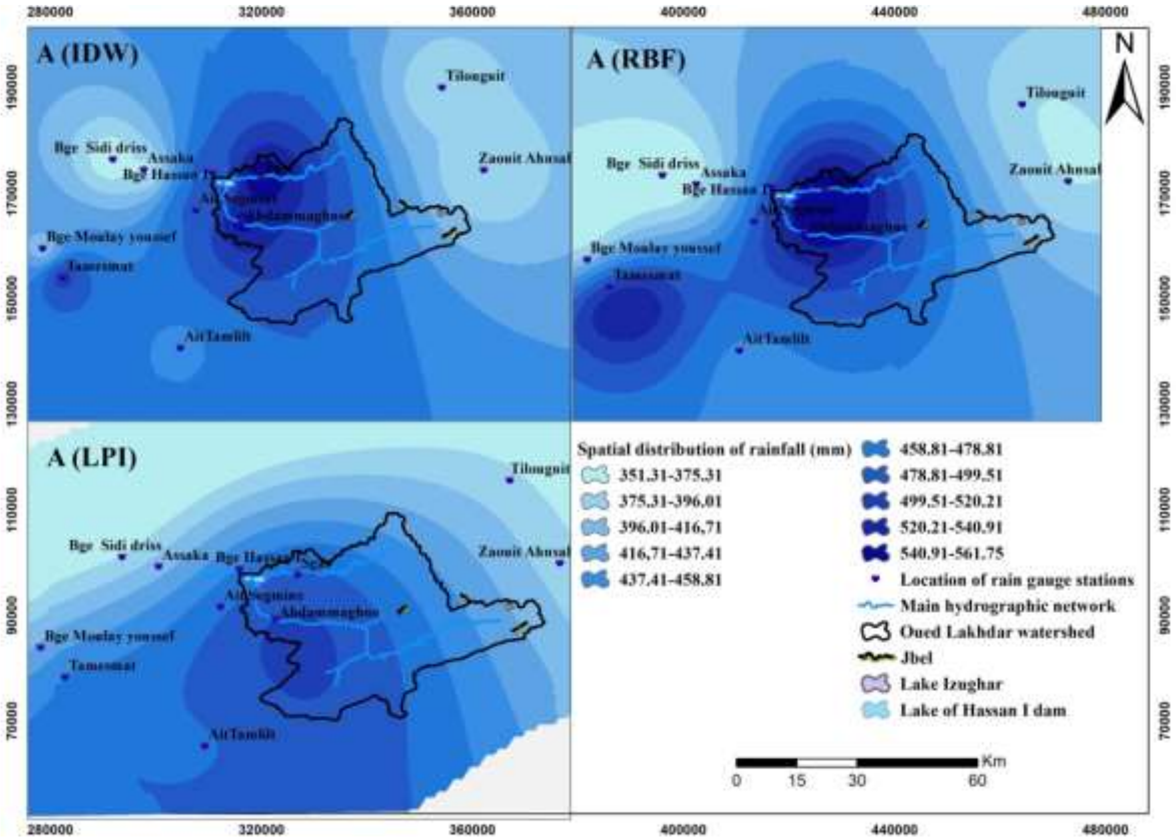


Figure 6. Annual precipitation spatial interpolation using empirical deterministic methods: (A) IDW; (B) RBF and (C) LPI

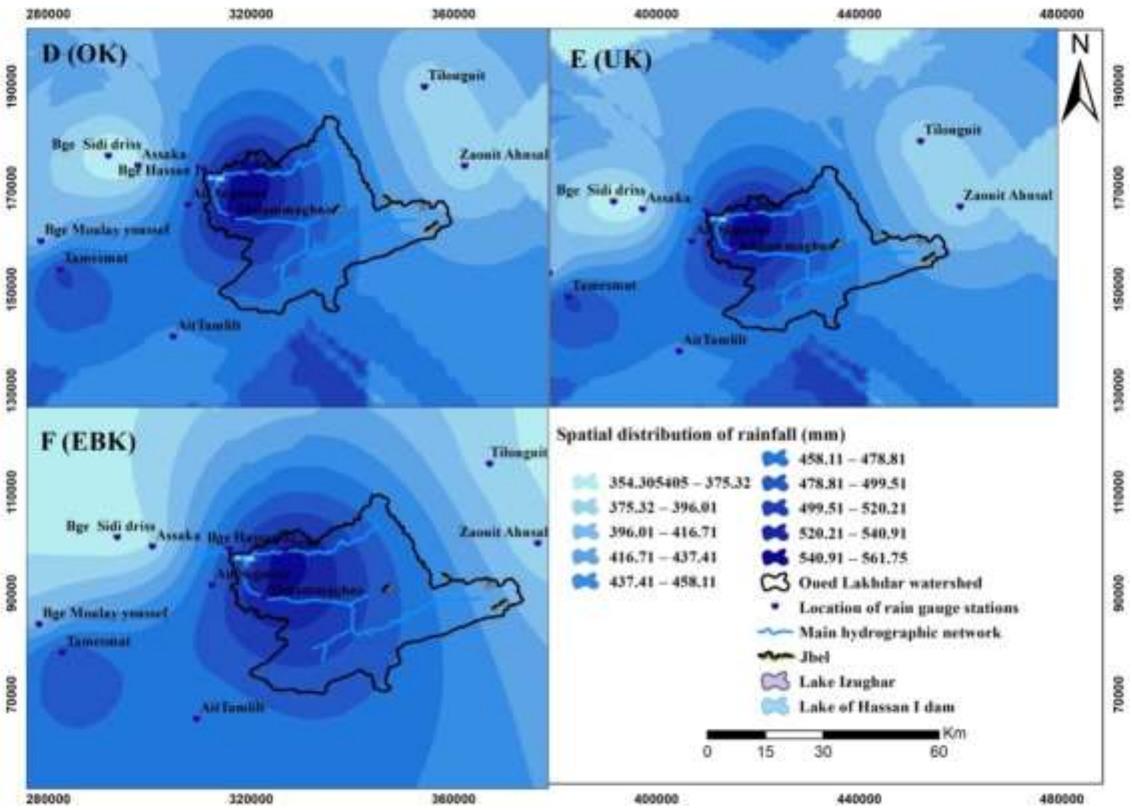


Figure 7. Annual precipitation spatial interpolation using probabilistic geostatistical methods: (D) OK; (E) UK and (F) BEK

In general, both figures show that precipitation is higher in the downstream part of the Oued Lakhdar watershed. In the upstream part of the basin, on the contrary, relatively lower levels of precipitation were recorded, indicating an abundance of solid precipitation in mountainous areas.

Conclusion

Because of the insufficient number of precipitation stations and the high cost of installing rain gauges in the Oued Lakhdar watershed, interpolation methods were used to spatialize precipitation on an annual scale. Two types of methods were evaluated: deterministic methods (RBF, LPI, and IDW) and geostatistical methods (UK, EBK, and OK). The comparison and cross-validation method (ME, RMSE, and R2) was used to select the optimum method for spatializing mean precipitation in this basin. The results obtained showed that interpolation using the UK method seems to correspond well to the realities encountered in the field. In contrast, the LPI technique revealed minimal correlation between the extrapolated and observed values.

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