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Optimal Rainfall Network based on GSMaP Satellite Product

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ملخص البحث:

تعتمد النمذجة الهيدرولوجية على قيم الأمطار التي تقاس بواسطة شبكات قياس الأمطار. كما جذبت قياسات الأمطار عن طريق الأقمار الصناعية اهتماماً كبيراً كمصدر آخر للمعلومات موثوق به. وبناءاً على هذا فإنه من الضروري وضع مقاييس الأمطار في المواقع المثلى وذلك لتحسين نتائج النمذجة الهيدرولوجية. يقدم هذا البحث طريقة لتحديد المواقع المثلى لوضع شبكات قياس الأمطار باستخدام بيانات الأقمار الصناعية والتي سيتم تطبيقها على وادي وتير. تم تطوير بعض الأكواد بلغة البرمجة Python ثم استخدمت للحصول على توزيع الأمطار اليومي وإجراء العمليات الحسابية. هذا وقد تم اختيار الأماكن المقترحة لإنشاء العديد من شبكات قياس الأمطار بطريقة عشوائية لاقتراح 150 شبكة مختلفة. وبهدف تقييم دقة هذه الشبكات المختلفة، تم استخدام عدة مقاييس أداء إحصائية. توضح النتائج أن شبكة معينة تحقق القيم المتوقعة لجميع مقاييس الأداء الإحصائية. بالإضافة إلى ذلك تشير النتائج إلى أن هذه المقاييس موزعة بشكل جيد حول الأجزاء الشمالية والجنوبية من وادي وتير. كما يتم رصد الأجزاء الوسطى والسفلى من الوادي بواسطة عدد مناسب من مقاييس الأمطار.

ABSTRACT:

Hydrologic modeling mainly depends on rainfall values which are measured by means of rain gauge networks. Additionally, the satellite products have recently attracted large attention as second and reliable source of information. Installing rain gauges in the optimal locations therefore is necessary to improve the results of hydrological modeling. In this paper, finding the optimal locations of a suggested rainfall network using the Global Satellite Mapping of Precipitation (GSMaP) is introduced and applied on Watier watershed. Python scripts were developed and used to obtain daily rainfall grids and to perform calculations. Selection of the proposed location of rain gauges is randomly created to generate 150 different rain gauges networks. Several statistical performance measures were used to assess the accuracy of these networks. Results illustrate that one particular network achieve the anticipated values of all measures. Additionally results indicate that the distribution of these gauges in the catchment is well distributed around the northern and southern parts. Middle and lower streams of the catchment are also monitored by reasonable number of rain gauges.

Keywords: Rain Gauge, Average Rainfall, GSMaP satellite product, Watier watershed

Introduction

In arid region, similar to what is found in Sinai Peninsula; the potential of rainfall occurrence is too rare over both time and space dimensions. However, when it occurs, it often causes destructive flash floods for many regions. Monitoring rainfall which is usually achieved by means of rain gauges network is therefore very essential and demanding task. The distribution of these rain gauges consequently has significant role to better understand the rainfall behavior of the region as well as improving the quality of the results of hydrologic modeling. Ensuring that these gauges are located in well representing sites to describe the rainfall distribution of an area is therefore as vital as suggesting new locations for rain gauges installation.

According to the World Meteorological Organization (WMO) recommendations for rain gauges network design, the area in square kilometers covered by one station in mountainous terrains should not be larger than 250 km^2 (WMO, 2008). In Sinai Peninsula, most of the rain gauges do not maintain this condition and the covered area by one gauge exceeds the mentioned value. As a result, there is a possible lack collected rainfall data especially when there are high variations in topography and rainfall occurrence. India for example has decreased the area covered by each gauge to 100 km^2 to accurately monitor the rainfall variation in complex terrain (Subramanya, 1994).

Alternately, rainfall could be monitored by the means of satellite products. The satellite products have recently attracted lots of attention due their powerful in both temporal and spatial resolutions. They cover large area in space and hence the rainfall distribution of any region could be attained. These products vary according to the technique, algorithm and the sensors which are used to monitor the rainfall. They also differ with each other with respect to spatial and temporal resolutions. Despite the success of satellite products, rain gauges are still required as they represent the ground truth of rainfall occurrence that even the satellite products use them to verify their accurateness. The GSMaP is broadly used in many researches and it is offered hourly in Near-Real-Time (NRT), available four hours after observation, using the JAXA Global Rainfall Watch System (Okamoto et al., 2005; Okamoto et al., 2007; Kubota et al., 2007).

In literature, several studies were done to assess the density of a rainfall network on the mean areal precipitation (e.g. Mishra, 2013); others have studied the effect of rain gauge density on interpolation technique selection (e.g. Otieno et al., 2014). Other studies have used optimization techniques to modify the locations of rain gauges or to increase/decrease their number (Awadallah, 2012; Volkmann et al., 2010; Pardo-igu, 1998). In general, this optimization may cause significant rainfall variability that will directly affect the hydrological modeling results. Several criteria of modifications employ the geostatistical approaches to resample the rain gauges network especially for the hydrological modeling purposes. For example, Barca et al. (2007) provided a methodology for assessing the optimal localization of new monitoring stations within an existing rain gauge monitoring network. Their proposed methodology uses geostatistics and probabilistic techniques (simulated annealing) combined with GIS instruments.

The aim of this work is to find the optimal locations of rain gauges to satisfy the WMO recommendations. The GSMaP_NRT Product will be used to achieve the objective of this study. The study area of this work is Watier watershed (3600 km^2) in south of Sinai Peninsula. According to WMO, it should be covered by 15 rain gauges to ensure that rainfall variation is well monitored.

Study Area and Rainfall data

Description of study area

Watier catchment is the second largest watershed in Sinai Peninsula in terms of area after El Arish watershed. It is located between 28° 45’ & 29° 30’ N and 33° 50’ E. The area of this watershed reaches to 3600 km^2 and it drains its floods runoff towards Aqaba Gulf (Figure (1)). In addition to the various tourism activities, this catchment receives its importance as it connects central regions in Sinai Peninsula to Nuweiba port, which is located on Aqaba Gulf, where the international road which extends for about 100 km in the main canyon of the basin from Nuweiba to Ras Al-Naqb cities. The most important villages in this catchment are Um Ahmed and Shiekh Attia while the major city is Nuweiba City, which is located at the outlet of the watershed.

The terrain of the watershed witnesses a large variations in terms of elevations and slopes where higher mountains spread out in the upstream of the basin staring at hilly slopes area at approximate elevation of 1600 m. The Wadi drops from the upstream plateau to sea level by means of a steep canyon (60 km). The average slope of the main wadi is about 0.81 %, but slopes up to 9.07% are encountered (Abdelkhalek et al., 2009). Because of the basin relatively large area, some studies tend to divide this watershed into small sub-basins. Mostly, this division is made to achieve the rapidness of the hydrological simulation. The main watershed consists of impermeable rock while its bed is highly permeable. The catchment area is dominated by basement rocks, mainly granites, which are highly fractured and intruded by basic dikes trending to North East – South West direction. The percentage of cracks in these rocks increases to large extent while the Quaternary deposits cover several areas of watershed's downstream.

The climate in this region hardly differs from Sinai Peninsula's climate which is characterized by extreme aridity. It is described by long rainless summer season and mild winter, however, high rainfall intensity in winter is likely to occur over several locations causing flash floods. Generally rainfall storms are prone to occur between the periods from December to May. The highest temperature in summer may exceed 40°C and the lowest temperature is about 4°C (WRRI, 2004). Despite the fact that this watershed is monitored by 9 rain gauges (W1, W2… W9) (Figure (1)), in this work, it was assumed that there is no information from ground measurements to suggest the optimal network.

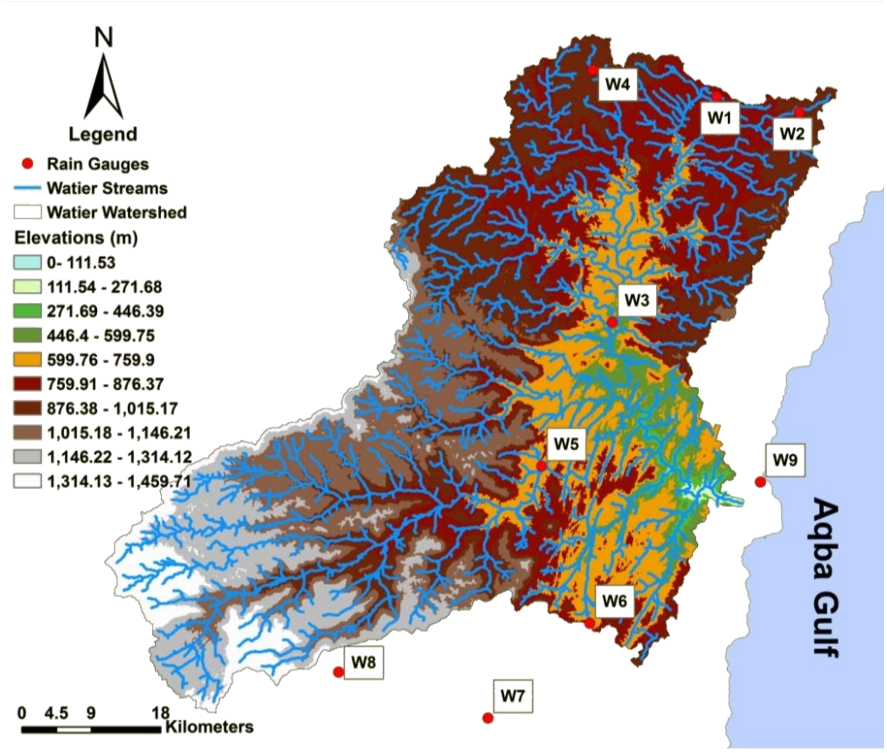

Figure (1): Study area, Watier watershed, showing currently existing rain gauges

Rainfall dataset

The rainfall data used in this study is obtained from Earth Observation Research Center (EORC), Japanese Aerospace Exploration Agency (JAXA). It is distributed from JAXA Global Rainfall Watch, which was developed based on activities of the GSMaP project (Okamoto et al., 2005; Okamoto et al., 2007; Kubota et al., 2007). It has to be mentioned that finding a correlation between this product and ground rainfall measurements is beyond the objective of this study and this task requires different scope of work as the results of this work concerned with the distribution of rainfall rather than the values.

This product was chosen because it maintains several merits. These advantages are (1) its availability four hours after observations (2) it covers whole globe (60 N – 60 S) with spatial resolution of 0.1 degree (10 km at equator) and (3) the temporal resolution of hourly based. These merits overlay with the requirements of this research where they fulfill a main condition of the spatial resolution which ensures that each grid value covers an area of effect of about 200 km^2 at equator, which is less than the area recommended by the WMO (250 Km^2) (WMO, 2008).

The hourly rainfall data was downloaded for 8 years between 2009 and 2016 (available period). For each day in this period, there are 24 grids representing the 24 hours of each day. As a result, this gives 70,128 rainfall grids for the whole period which will be used in the analysis.

Methodology

In this work, the GSMaP product will used to find the optimal locations of rain gauge for Watier watershed. GSMaP raw data was converted to a relevant format which can be used in this analysis. Hence, data was converted from ASCII to TIFF format. This format is accessible by ArcGIS and it could be used for several operations. The grid distribution around the watershed allows to select relevant number of cells representing the watershed area. As a result, (50) points, each one is the center of cell in the grid, were selected to represent the watershed (**Figure (2)**). The hourly rainfall data was then extracted from the satellite product at the locations of those points and stored showing the date of that event. Using the developed Python scripts, it was possible to loop through the whole period between 2009 and 2016 to obtain the daily rainfall data grids. This would result in 93 days of rainfall data for the whole period after removing the non-rainy days.

To achieve the WMO recommendations, 15 rain gauges should be distributed over this watershed. Hence, 30% of the selected points (50 points) have to be designated. This raises a key question: which 15 points should be chosen? To answer this question, Python scripts were used again to randomly select the 15 points among the total number. Given the possible number of options, it was difficult, if not possible, to create all possible networks. Therefore, and in order to find the optimal distribution of these points, 150 random networks were created. The average rainfall over the watershed is then computed for each network for all the given 93 days. The interpolation method used to get this average is the well-known method, the Inverse Distance Weighting. The resultant average rainfall over the catchment will be assessed with respect to the average rainfall estimated using all the 50 points.

To find the optimal network configuration, several statistical measures were used to calculate the errors. These are the Root Mean Square Error (RMSE), Nash–

Sutcliffe efficiency (NSC) and Mean Absolute Error (MAE). The optimal network is therefore should achieve the lowest value for RMSE and MAE and the highest values for NSC. The equations of these measures are shown in Equation (1) Equation (2) and Equation (3) respectively.

$$RMSE_n = \sqrt{\frac{1}{k}\sum_k (R_n - R_i)^2} \qquad \textbf{Equation (1)}$$

$$NSC_n = 1 - \frac{\sum_k (R_n - R_i)^2}{\sum_k (R_i - R_i^{m})^2} \qquad \textbf{Equation (2)}$$

$$MAE_n = \frac{1}{k}\sum_k |R_n - R_i| \qquad \textbf{Equation (3)}$$

where (k) is the total number of days, (i) is the total number of points existed over the watershed (i.e. 50), (R) is the average rainfall over watershed computed at each network (n) which it takes the values between (1 and 150). (m) is the mean value of the average rainfall computed for the total number of rain gauges existed over the watershed.

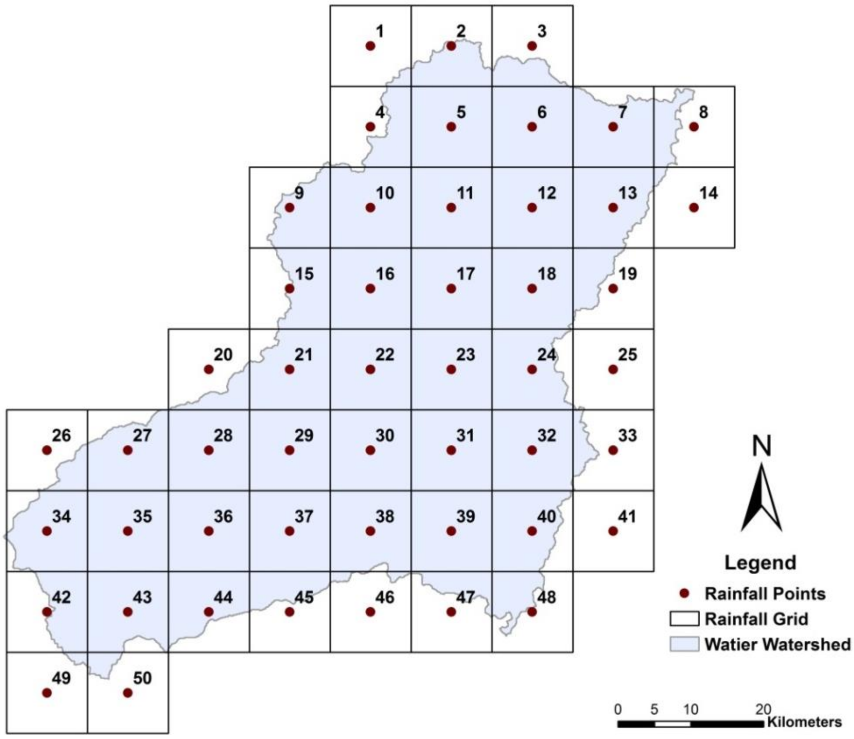

Figure (2): Selected grid points representing Watier watershed, showing 50 points where each one is located at the center of each cell

Results and Discussion

Statistical properties of the 150 networks

After computing errors in estimating the average rainfall for the 150 networks, the description of the estimated statistical performance measures is introduced. The statistical properties given hereafter are given with respect to the all 150 networks that were investigated in this analysis. **Figure (3)** shows these statistical properties for the performance measures (RMSE, MAE and NSC) of the 150 networks. It includes the minimum, average and maximum values. Furthermore, some basic statistics such as the standard deviation, variance, skewness and excess kurtosis (referenced to normal distribution) are shown.

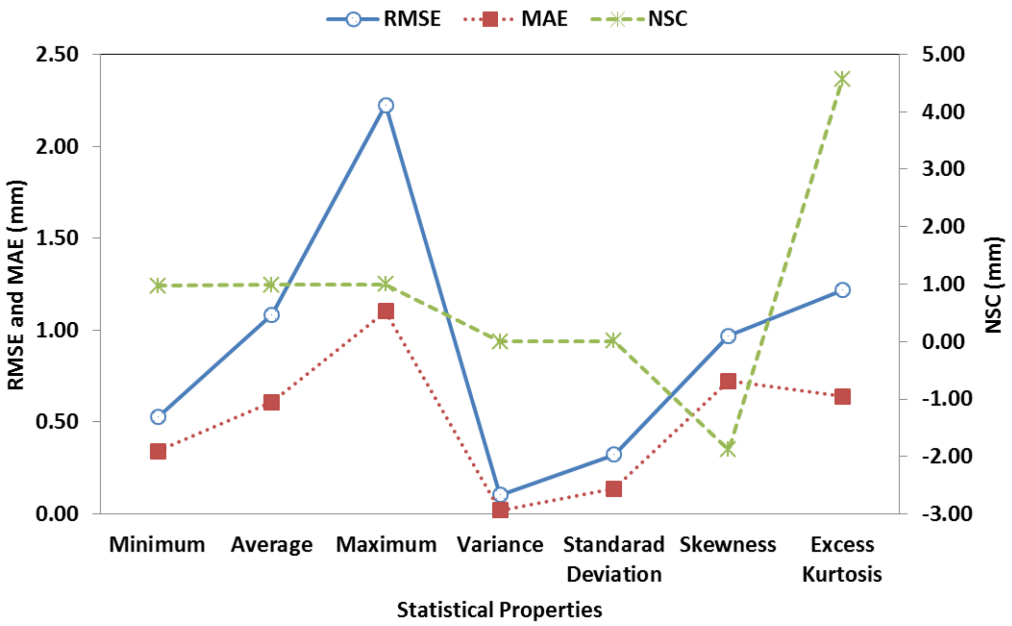

Figure (3): Statistical properties of the performance measure of the 150 networks

It can be observed from the figure that almost NSC values for the entire 150 networks have constant value where the minimum and maximum values are nearly 1.0 mm. Unlikely there is little differences for the RMSE and MAE. The maximum RMSE exceeds 2.00 mm while it exceeds 1.0 mm for MAE. However, the minimum values of each of them are very close to 0.50 mm. The variance value for all the measures are very close to 0.0 which implies that differences among the errors of average rainfall values among all 150 networks is negligible.

Moreover, skewness values refer to that errors distribution seem to follow a flatter distribution as their skewness values are larger than 1.0. Positive and negative signs indicate whether the distribution of the data is skewed right or left respectively. Furthermore, kurtosis values refer to the height and sharpness of the peak relative to the rest of the data. Higher values (>0) indicate a higher, sharper peak whereas lower values (<0) indicate a lower, less distinct peak. Again the RMSE and MAE seem to have sharper while NSC can be rejected as its value exceeds 3.0.

The probability of exceedance can be defined as the number of times that a stochastic process exceeds some critical value (Hobilt, 1988). In this section this critical value is estimated for the given probabilities for every statistical measure. Consequently, the maximum value of error for each statistical measure could be identified. **Figure (4)** shows the exceedance probability of the RMSE, MAE and NSC for all the 150 networks. It can be noticed from the figure that the critical value of the NSC does not change with changing the exceedance probabilities. This is expected as there is no variations of its values as explained earlier. The critical value of the MAE ranges between 0.4 and 0.8 mm while it increases for the RMSE to range between 0.6 and 1.50 mm. This means that for Watier watershed, for example, the probability that the RMSE exceeds the value of 1.50 mm is 10%.

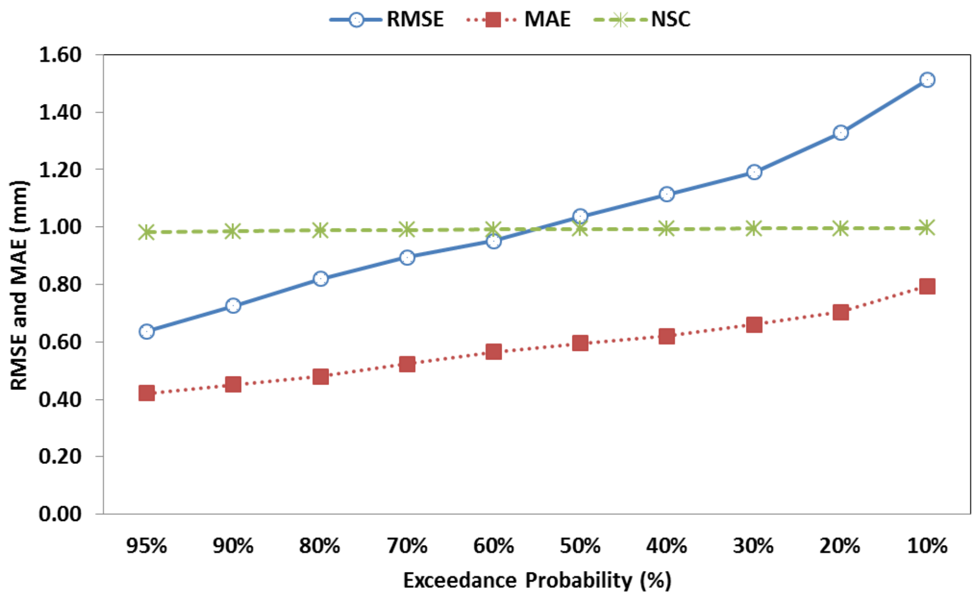

Figure (4): The Exceedance probability in (%) of the performance measure for the 150 networks

Optimal rain gauge network

As mentioned earlier, there are 150 networks representing the average rainfall over the catchment. After calculating the statistical measures for each network, it was necessary to find the optimal one that will be suggested over Watier watershed. This was achieved by finding the network that achieves all the anticipated values of the performance measures (i.e. minimum of RMSE and MAE and maximum of NSC). **Figure (5**) illustrates the values of these measures for all the 150 networks, arranged from the smallest to largest according to the RMSE values. It can be observed that there is a matching between the order for both RMSE and NSC. Only MAE shows dissimilar orders especially when moving upward in ranking however, it remains the same at the beginning as indicated by

Table (1). This table shows the values of these measures for the first 3 groups after sorting them according to the RMSE values.

Table (1): The values of statistical performance measures for the optimal network

Optimal Network	RMSE	MAE	NSC
G 57	0.528	0.340	0.998
G107	0.560	0.379	0.997
G137	0.596	0.368	0.997

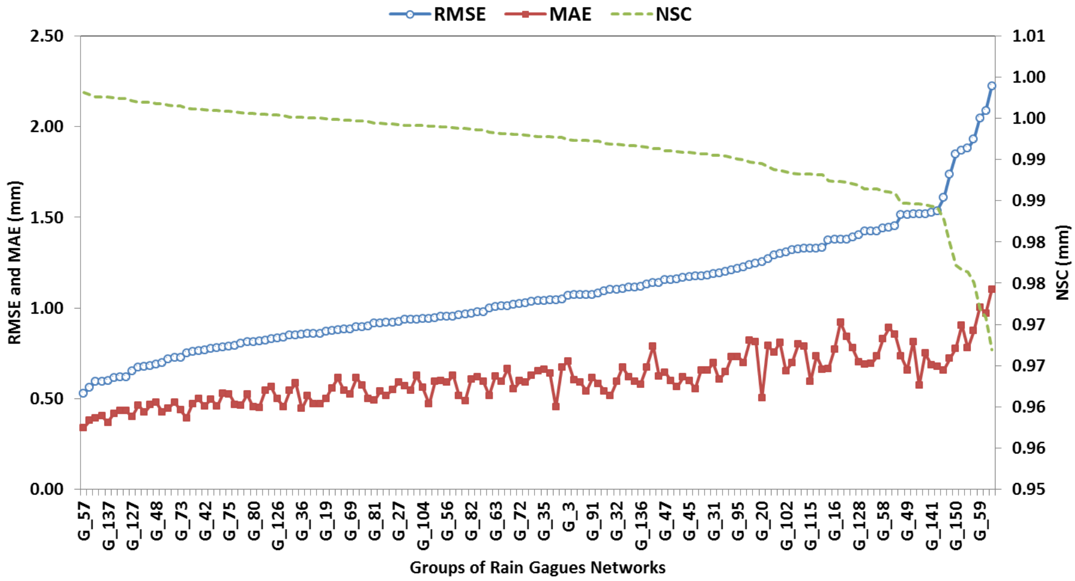

Figure (5): The RMSE, MAE and NSC for the 150 networks, sorted based on the RMSE values from the smallest to the highest

For visual illustration of the optimal rain gauge network, **Figure (6**) illustrates the geographical distributions of the optimal network for Watier watershed. It can be observed from the figure that the rainfall network distribution can be divided into three groups. The first one which consists of points (17, 22, 23 and 32) covers the middle part and the lower streams network of the catchment. The second are concentrated in the northern side of the catchment and it includes points (3, 4, 6, 8, 9 and 18). While the last group of points (34, 36, 37 47 and 49) are spread out in the southern part of the catchment and they spread out as it extends horizontally.

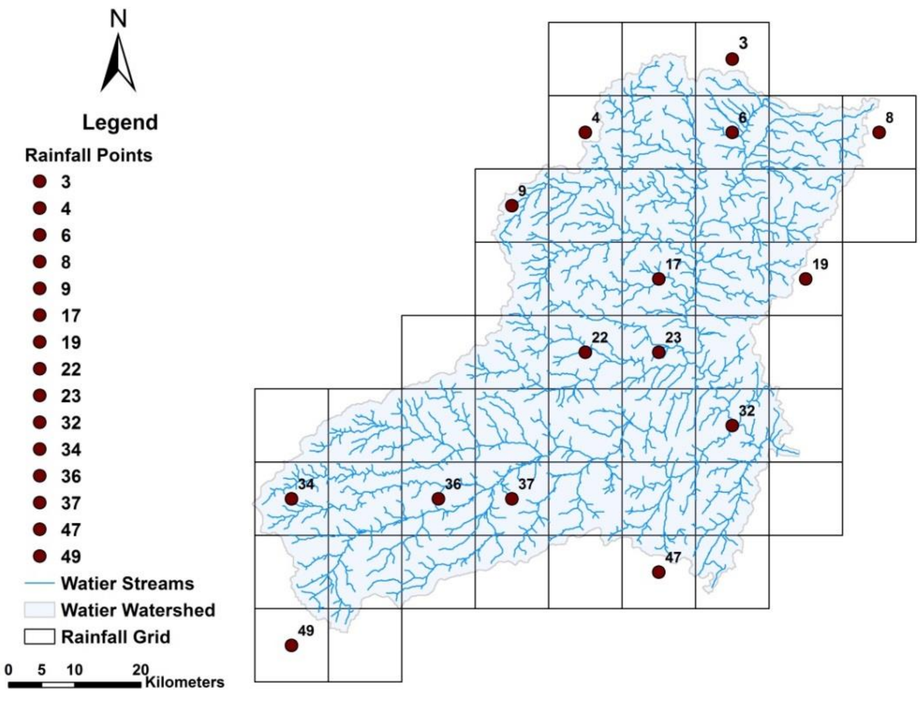

Figure (6): The spatial distribution of the optimal rain gauge network in the catchment

Conclusion

This paper aimed at finding the optimal locations of rainfall network over Watier watershed. The proposed number of rain gauges of this network is selected to satisfy the recommendation of the WMO. The hourly rainfall data retrieved from GSMaP satellite product between 2006 and 2016 was used to achieve the requirements of this research. Python scripts were efficiently used to obtain daily rainfall grids for the whole period of data and to perform the calculations. One hundred and fifty different rainfall networks were randomly created to find the optimal distribution of rain gauges. Three statistical performance measures were used to estimate the error in average rainfall values for each network. The errors are computed with respect to the average rainfall value computed using the original number of points (50 points). Results show that one particular group of points achieve all the performance measures. The spatial distribution of these gauges in the catchment shows that they are well distributed around the northern and southern parts. Middle and lower streams parts of the catchment are also monitored by reasonable number of rain gauges.

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