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Effect of Rainfall Gauges Density on Areal Reduction Factor

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Abstract:

Rainfall ground gauges measure the rainfall depth only at a certain physical point which is the location of the gauges. However, storm events are a natural phenomena with an intensity varying between a maximum value at storm center and decreases to zero at the storm event peripheries. To account for this variability, usually the maximum rainfall value is multiplied by a ratio – less than unity – termed the Areal Reduction Factor (ARF), that is usually a function of area, to reduce the design rainfall value when considering an areal average instead of a point value.

As most of catchment areas have only limited rainfall gauges due to capital and running costs of these gauges, it is important to account for the number of gauges and / or the distance between stations or their areal coverage when using the ARF ratios. The purpose of this paper is to investigate the relation between the number of stations in the context of an arid or semi-arid watershed and identify correction factors needed to be applied for areal reduction factors calculated using limited number of gauges. Many researchers studied the areal reduction factor estimate; however, the relation between the number of gauges used in developing areal reduction factor equations and its value was not investigated.

In this study, rainfall records from 90 gauges in Walnut Gulch, USA, experimental watershed were used to study the impact of the rainfall gauges density within a watershed on the value of the deduced areal reduction factor. Eight groups were selected to represent the rainfall gauges intensity, which are 3, 6, 10, 20, 40, 50, 70, and 89 gauges. For each group, 1000 samples, each with the previously mentioned number of stations, were made using the orthogonal sampling technique. For each group, the areal reduction factor was calculated and an average ARF curve is estimated. Results were compared to the ARF deduced using the full set of 90 gauges. It was found that the areal reduction factor values decrease proportionally with the increase of the rainfall gauges density. Correction factors curves were generated to be used as a function of rainfall gauges intensity.

Keywords - ARF, Areal Reduction factor, Orthogonal sampling, ARF correction factor

I. INTRODUCTION

Accurate estimation of runoff quantity is an important target for researchers and engineers as it affects the feasibility studies of governmental and private projects, this effect increases proportionally with the project scale. The importance of accurate estimation of runoff is that although over estimation of runoff will fulfil safety aspects, it will also entail economic aspects where more money is being invested which could have been saved for other investments.

Reviewed publications did not relate the availability of dense rainfall gauges on the estimation of the areal reduction factor. This is mainly because it is hard to find dense rainfall gauge networks. However, dense networks of rainfall gauges will definitely simulate a storm within a catchment much better than catchments with low density gauges networks and the probability of catching the storm center with its peak value is also increased. This is because rainfall gauges measure the point rainfall depth that occurred at the location of the gauge.

Areal reduction factor is a factor that is used in rainfall estimation and it represents the ratio between the average rainfall depth over an area to the point rainfall depth. Several researchers studied areal reduction factor to identify the factors that influence its value. Previous researches presented hereafter are organized according to three topics; factors affecting areal reduction factors, minimum and maximum areas where ARF is significant, and methods to calculate areal reduction factors.

Desbordes et al. [1] studied areal reduction factor on short time and space intervals and concluded that the areal reduction factor varies with storm duration.

Skaugen [2] studied the type of daily rainfall events in Norway and classified it into two categories; the first category is the convective storms and the second category is the frontal storms. Skaugen [2] concluded that frontal rainfall is not much affected in magnitude when the area is increased, while convective rainfall, with a smaller scale, is showing reduced magnitude when the area is increased. Skaugen [2] also found that areal reduction factor is more significant with high return periods.

Prudhomme and Reed [3] studied the effect of wind direction in mountainous areas. They clarified that Thiessen polygon and inverse distance methods do not directly account for topography. They commented that this is because rain gauges networks are mostly sparser at areas with high elevation and they may not represent areal precipitation adequately.

Asquith and Famigiletti [4] concluded that the rainfall record length may affect the ARF estimates and they have also concluded in their study in Huston, Texas, that three overlapping networks gave different estimates for the ARF. They have related this to the temporal variability of the rainfall.

Vaes et al. [5] have studied the areal reduction factors on a small scale catchment in Belgium and stated that there are two types of factors: the first type is the commonly known reduction factor that compensates for the difference between point rainfall that is measured at the gauge and average rainfall which actually precipitated over the catchment, the other type they developed is a correction factor for rainfall to consider historical rainfall records. However, this study was based on a computer model rainfall simulator rather than actual data. In their study, they have concluded that correction factors for historical data (which are needed for model calibration purposes) may be even more than 1 unlike the common areal reduction factors (less than 1) which their results proved that it is dependent on return period.

Allen and DeGaetano [6] have related the areal reduction factor to the seasons in which they found that areal reduction factor is more effective in cold seasons than warm season. They have justified as convective storms are more in cold seasons. In their study, they have also concluded that the effect of differences in station density and interpolation method used is not affecting ARF estimates. This conclusion specifically will be debated in this study performed on Walnut Gulch, Arizona, USA, watershed in which orthogonal sampling technique was introduced on a dense gauge network.

Ramos et al.[7] investigated rainfall in Marseille, France and studied the events with durations from 6 to 90 minutes. They pointed out that areal reduction factors in short duration rainfall decrease more rapidly with increasing areas when compared to long durations rainfall events.

Veneziano and Langousis [8] studied the effect of the catchment shape on the ARF and according to their study findings the relation between the catchment shape and the ARF was found to be very small. They also pointed out that elongated watersheds are rare and thus catchment shape should not be of a great concern.

Srikanthan [9] identified an approximate area limit of 4 km^2 for which the intensity of point rainfall will is applicable. Thus, for several rainfall gauges in a watershed the measured rainfall depth will vary from a gauge to another and this variability will increase with the increase of the watershed area.

Luyckx et al.[10] have concluded that one rainfall event can have a variation for the rainfall with a standard deviation of 2.5km which, for large catchments, lead to major difference between actual and predicted rainfall amounts. This means that for catchment with few gauges, the actual peak of the storm, or even a close precipitation value, may not be observed.

Clark and Rakhecha [11] studied the probable maximum precipitation for the safe construction of dams and spillways. In their study, they concluded that ARF for areas of 10 to 20,000 km^2 are ranging from 1 to 0.41 and is not affected by the duration of rainfall.

Mineo et al. [12] studied the effect of return period on ARF in Lazio region, Italy. Results suggested that for the durations less than 3 hours, the effect of the return period on the ARF is very small when the area is ranging from 1 to 100 km^2, and this effect vanishes when the area increases further. Moreover, the results also showed that, for durations between 3 and 6 hours, the return period does not affect the estimation of the ARF. As such, Mineo et al. concluded that it can be considered a conservative approach to use the low return period while estimating the ARF.

II. ESTIMATION OF AREAL REDUCTION FACTOR

Estimation of the areal reduction factor can be done using empirical methods which can be subdivided into two categories; storm-centered approach and fixed-area approach [13]. Examples for these methods are the US Weather Bureau method, the annual maxima centered method, and the storm movement method. Estimation could be either performed using ground gauges data or radar data.

The storm centered approach depends on the center of the storm, which is not the same in each event. The areal reduction factor based on the storm-centered approach is defined as "equation 1" below:

$$ARF = \frac{P_{Area}}{P_{Point}} \quad (1)$$

where P_{area} is the average rainfall for a given area enclosed by a certain rainfall contour (isohyet) and P_{point} is the maximum rainfall depth at the storm center.

Unlike the storm-centered approach, the fixed-area approach computes the ratio between an average rainfall depth value over the whole catchment (as a fixed area) and the point maximum rainfall value for the area under study. According to [14], an advantage for the fixed-area approach over the storm-centered approach is that the latter is not correct when estimating areal rainfall of a specific return period. This is due to the fact that extreme point events and extreme areal events are not commonly to happen from the same rainfall event. Omolayo [14] suggested to enhance the statistical probability of having more accurate results for estimating ARF through introducing the storm return period in the equation.

The US Weather Bureau method is one of the most common methods to calculate the areal reduction factors that is widely used in the US. It was developed by the U.S. Weather Bureau in Technical Paper no. 29 [15]. Like many other empirical methods, the US weather Bureau method has considered that the estimation of ARF is independent of the return period. However, this effect was acknowledged in other researches. The equation of ARF estimate based on the US Weather Bureau method is written as "equation 2" below:

$$\boldsymbol{ARF = \frac{\sum_j \sum_i w_i P'_{ij}}{\sum_j \sum_i P^{i.j}}} \quad (\mathbf{2})$$

where

w_i is the Thiessen weighting factor w_i for each rainfall station i

P_{ij} is the annual maximum point rainfall in a duration D at station i in year j

P'_{ij} is the point rainfall in a duration D at station i on the day when the annual maximum areal rainfall occurs in a year j, Pi precipitation in a gauge (i) in the region

III. STUDY AREA AND AVAILABLE DATA

The Walnut Gulch Experimental Watershed (WGEW) is a research watershed extended 150 Km^2 in south eastern Arizona, USA. Fig 1 below shows the watershed within its main basin "the upper San Pedro River" which extends also for another 7600 square kilometers in Sonora, Mexico and Arizona. The study area is classified as a semi-arid region at is dry almost 99% of the time and it is considered as an intermediate "transition" region between the Chihuahuan and the Sonoran Deserts. The ground elevation within the watershed ranges between 1250 m and 1585 mMSL.

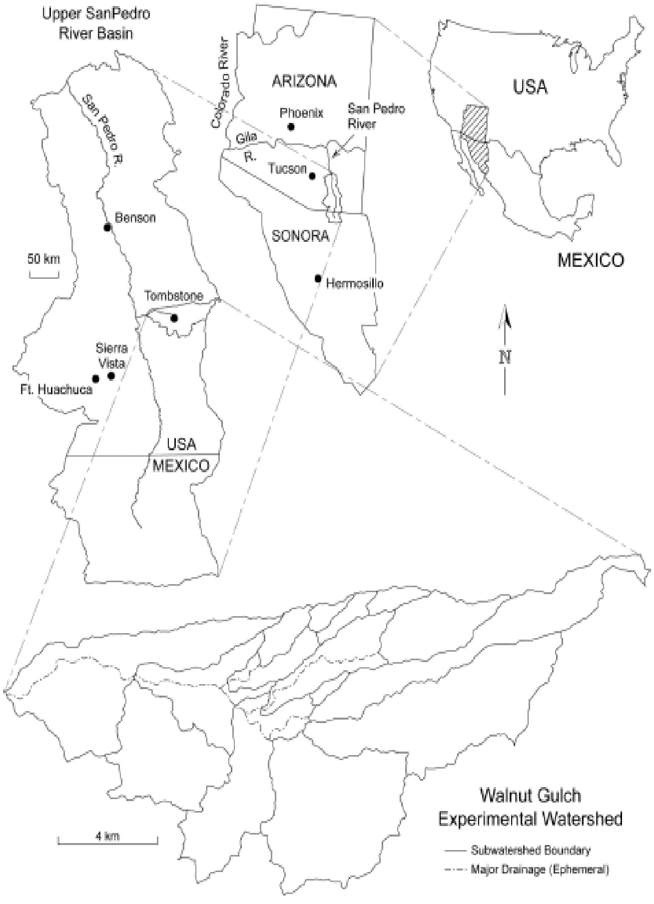

Figure 1. Walnut gulch experimental watershed (after [16])

Data of the watershed, which is available on [17] include precipitation, runoff, sediment, meteorological and soil moisture data. Precipitation is measured via a network of 88 weighing-type recording rain gauges arranged in a grid throughout the watershed. Two additional gauges are lying adjacent to the watershed borders and where also used in the analysis giving a total of 90 gauges [18].

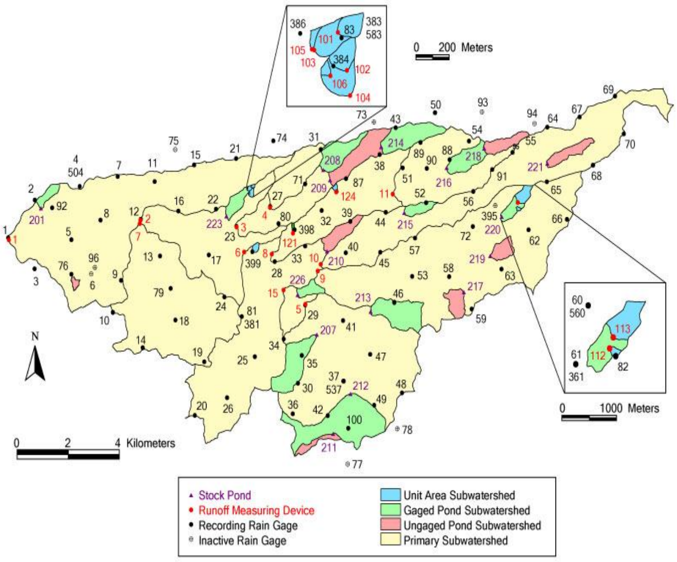

Figure 2. Rainfall and runoff gauges location for Walnut Gulch (after [16])

IV. METHODOLOGY

IV.I. EXPLORATORY ANALYSIS

Areal reduction factor curves are calculated for individual storms using the entire 90 gauges. Comparison is undertaken between extreme storms and ordinary ones. It is found that the pattern of ARFs are significantly different between the two groups. It is decided to focus on extreme storm events, since ARFs are usually used in the context of design purposes dealing with extreme events. The maximum 50 events in terms of average rainfall are identified and over 800 isoheytal maps using the rainfall records of the 90 rainfall gauges of Walnut Gulch watershed are analyzed. The 800 maps are divided to 8 groups, each group containing 100 samples with the same size but with various combinations of the gauges. Samples sizes are 3, 6, 10, 20, 45, 50, 70 and 89 gauges respectively and for each sample size 100 combinations are created. Each group is denoted as ARFx where x is the sample size of the 100 combinations in this group.

IV.II. SAMPLING

MATLAB software is used to generate a numerous number of samples via the embedded orthogonal sampling code. Orthogonal sampling is achieved through dividing the set of data to a number of quantiles equal to the required size of sample and then the code chooses a random number from each quantile.

To ensure that all samples are adequately covering the catchment area, the catchment area is divided into 6 zones (called hereafter groups), geographically selected based on the number of gauges in each group while maintaining a reasonable relative coverage area for all groups compared to each other. Moreover, the gauges are numbered based on the identified groups so that all gauges in one group have consecutive numbers before moving to the next group. Gauges are then arranged in ascending order. This procedure is adopted to ensure that the random selection, performed by the orthogonal sampling, will have an acceptable distribution over the entire catchment.

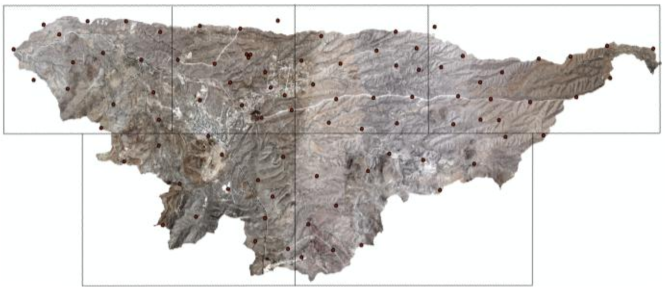

Figure 3. Gauges grouping

IV.III. ARF calculations

Areal reduction factor is calculated using a typical fixed-area approach in which the average rainfall depth over an area subject to a certain depth of rainfall is compared to the maximum rainfall depth, at theoretically the storm center, using the following "equation 3" below:

$$ARF = \frac{P_{Area}}{P_{Point}} \qquad (3)$$

An increment of 1mm of rainfall depth is used to calculate P_{area} and then divided by the maximum rainfall depth for the event to calculate the ARF volume for a certain event based on a certain gauge combination as follows;

- Minimum and maximum recorded rainfall depth are identified in each event.
- An isoheytal map is drawn in GIS for this event.
- Starting from the minimum rainfall depth, a plane (level), is identified and the rainfall volumes (rainfall depths multiplied by their corresponding areas) exceeding the starting depth are calculated. The minimum rainfall depth is then increased by an increment of 1mm and the procedure is repeated till reaching the maximum rainfall depth.
- The total rainfall volume is divided by the area to get the average rainfall depth above this plane.
- The average rainfall depth is divided by the maximum rainfall depth to obtain the ratio of the average rainfall (over a certain area) to the maximum point rainfall.

The same procedures described above are repeated for all samples for each station number group and ARFs are calculated. Fig 4 illustrates a sample of the calculation output of ARF corresponding to a certain rainfall event and a certain sample made of a specific number of stations: On the other hand, Fig 5 shows a sample of isoheytal maps generated for a certain rainfall event also, however, for a certain sample made of a specific number of stations for the study area.

ARF

Plane Level mm	Area 2D m^2	Area 3D m^2	Volume m^3	Volume/Area mm	Volume/Area+Plane Level mm	Divide by max of previous column	Area 2D (sq.km.)
28.960	87,696,675.000	87,697,297.408	910,862,598.740	10.387	39.347	0.542	87.697
29.000	87,584,057.947	87,584,680.353	907,357,080.491	10.360	39.360	0.542	87.584
30.000	84,644,794.057	84,645,414.816	821,196,959.383	9.702	39.702	0.547	84.645
31.000	78,516,190.399	78,516,806.816	738,955,890.349	9.412	40.412	0.557	78.516
32.000	61,199,422.654	61,200,032.674	667,126,220.144	10.901	42.901	0.591	61.199
33.000	47,625,544.865	47,626,149.796	612,289,340.433	12.856	45.856	0.632	47.626
34.000	37,708,633.096	37,709,232.544	571,247,046.990	15.149	49.149	0.677	37.709
35.000	35,003,903.935	35,004,496.648	534,966,185.257	15.283	50.283	0.693	35.004
36.000	32,922,967.808	32,923,552.125	501,038,191.772	15.219	51.219	0.706	32.923
37.000	31,176,093.869	31,176,668.259	469,010,341.620	15.044	52.044	0.717	31.176
68.000	2,624,719.391	2,624,737.192	6,193,213.074	2.360	70.360	0.969	2.625
69.000	2,070,826.952	2,070,837.936	3,845,847.098	1.857	70.857	0.976	2.071
70.000	1,519,324.021	1,519,329.801	2,050,756.479	1.350	71.350	0.983	1.519
71.000	963,880.757	963,882.981	808,475.891	0.839	71.839	0.990	0.964
72.000	392,578.848	392,579.184	128,090.106	0.326	72.326	0.996	0.393
72.540	65,475.743	65,475.751	3,319.885	0.051	72.591	1.000	0.065

Figure 4. Sample of calculation of ARF corresponding to a rainfall event

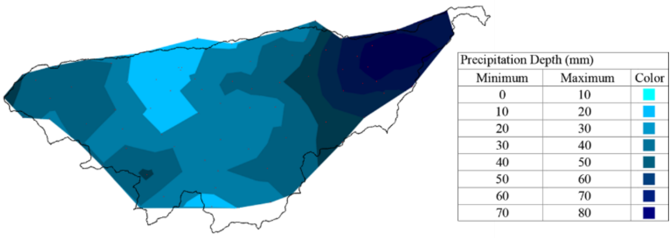

Figure 5. Sample of generated isoheytal maps

V. RESULTS AND DISCUSSION

It is necessary to ensure that the arrangement performed on the data, before sampling, is efficient in forcing an appropriate distribution of stations. An appropriate distribution of stations in a certain sample will result in stations spread not close to each other, similar to what a rainfall network design could have located the stations. This is essential for the applicability of ARF proposed correction charts when the number of available stations is small. Fig 6 hereafter illustrates an example of coverage of 10 successive samples, in which each sample is simulated with a circle of specific color and size. It is noted that the samples are distributed with an acceptable coverage across the watershed.

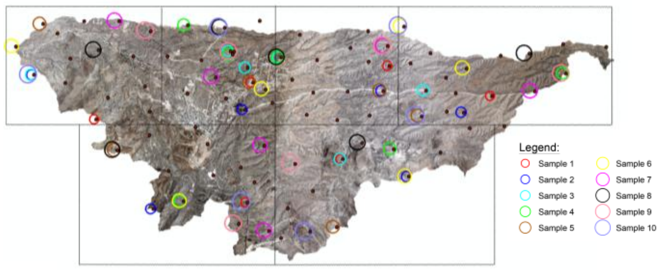

Figure 6. Sampling distribution efficiency

V.I. NUMBER OF SAMPLES

After creating the samples using the orthogonal sampling technique, it is necessary to identify the acceptable number of samples that can be used without compromising the results in order to cutdown the time of processing of the isoheytal maps and calculating the ARFs.

We investigated the variation in the ARF calculations based on 100 and 200 samples to determine whether there is considerable variation in the results or whether the 100 samples for each rainfall density will be sufficient to obtain robust results. The ARFs resulting from a group of 10 gauges are checked based on 100 and 200 samples. Since there is a variation in ARFs between samples (due to the variation in stations in each sample), we report hereafter the differences between the 100 and 200 samples in terms of percentiles. The change in results did not exceed 0.83% for the 10% percentile while the percentages are much smaller for larger percentiles.

Table 1: Change in ARF for 100 and 200 samples

Area (Km^2)	**ARF % change for data percentiles**				
	10%	**25%**	**50%**	**75%**	**90%**
0.5	0.03%	0.02%	0.01%	0.01%	0.00%
1	0.04%	0.03%	0.02%	0.02%	0.00%
1.5	0.06%	0.05%	0.02%	0.03%	0.00%
2	0.09%	0.06%	0.03%	0.03%	0.01%
2.5	0.10%	0.06%	0.03%	0.03%	0.01%
↓	0.14%	0.05%	0.04%	0.03%	0.01%
	0.16%	0.07%	0.04%	0.03%	0.01%
	0.17%	0.09%	0.05%	0.03%	0.01%
	0.19%	0.10%	0.05%	0.03%	0.01%
145.5	0.12%	0.20%	-0.03%	0.07%	0.06%
146	0.11%	0.24%	0.08%	0.00%	0.02%
146.5	0.01%	0.14%	0.03%	-0.04%	0.00%
147	0.00%	0.14%	0.03%	-0.05%	0.00%
147.5	-0.01%	0.14%	0.03%	-0.05%	0.00%
148	-0.18%	-0.01%	-0.06%	-0.07%	0.01%

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Based on the above, 100 samples are adopted for each density group. A portion of the comparison between the 100 and 200 samples is shown in Table 1. The ARFs are generated using the described methodology are plotted in Fig 7 to Fig 9.

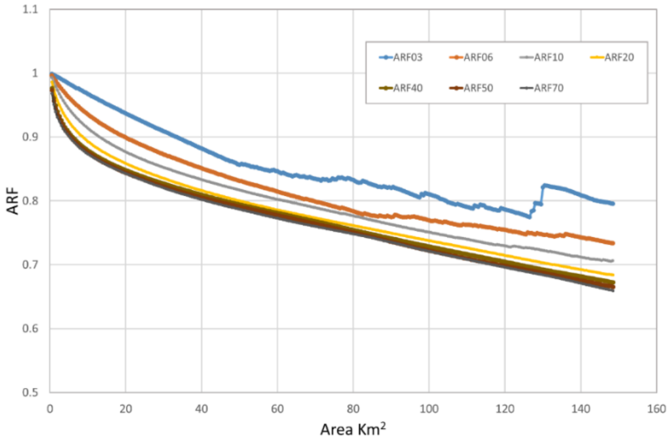

Figure 7. ARF for various groups at 50% percentile

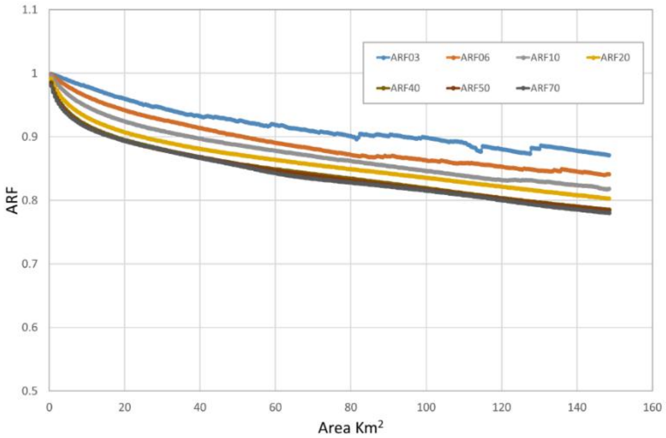

Figure 8. ARF for various groups at 75% percentile

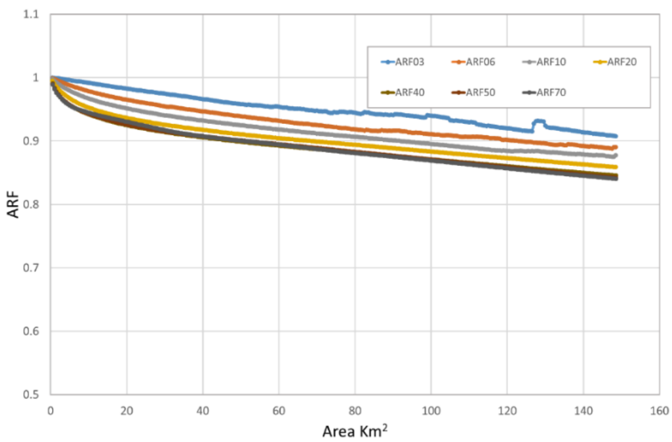

Figure 9. ARF for various groups at 90% percentile

As illustrated in Fig 7 to Fig 9, ARF curves generated from a group of 3 gauges show some fluctuations in the results, with curves not monolithically decreasing. These fluctuations increase with the increase of the area. The curves generated from 6 gauges show less fluctuations and the start of the fluctuations begin at a larger area. The same is noticed for the ARF generated from the group of 10 gauges. This can be explained by the fact that, when the area increases, the required number of gauges to have an appropriate estimate of the areal reduction factor increases. In other words, the density of the rainfall gauges affects the estimated values of ARF.

It can be also noticed from the graphs that the ARF curves generated from 40, 50, and 70 gauges are almost identical, which means that increasing the number of gauges excessively will not enhance or affect the ARF results after reaching a certain threshold rainfall gauges density. This conclusion could help in optimizing the capital cost of building rainfall gauges.

V.II. NONLINEAR FITTING OF ARF CURVES

ARF values are calculated with increment area of 0.5Km^2 starting with the smallest area of 0.5km^2 to 148.5 km^2 which is the total area of the watershed. Nonlinear regression between the area and the ARF values for all rainfall density groups is developed in the form of the following equation. The fittings are undertaken for 50% percentile and 90% percentile curves.

$$ARF = 1 - b \times Area^{a} \quad (4)$$

where

ARF is the estimated Areal reduction factor

a and b are nonlinear regression coefficients

Area is the area of watershed at which ARF is estimated (km^2)

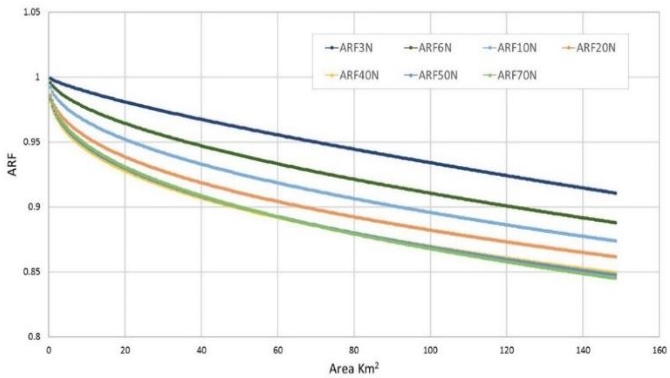

Figure 10. Nonlinear regression for ARF curves for 90% percentile

As described earlier, ARF curves generated from samples with gauges more than 40 are discarded as the curves are almost identical as in Fig 10 above. Fig 11 and Fig 12 illustrates the fitting of the ARF curves using nonlinear regression, while Table 2 and Table 3 summarize the regression factors and equations of ARF curves for the density groups 3, 6, 10, 20, and 40 rainfall gauges.

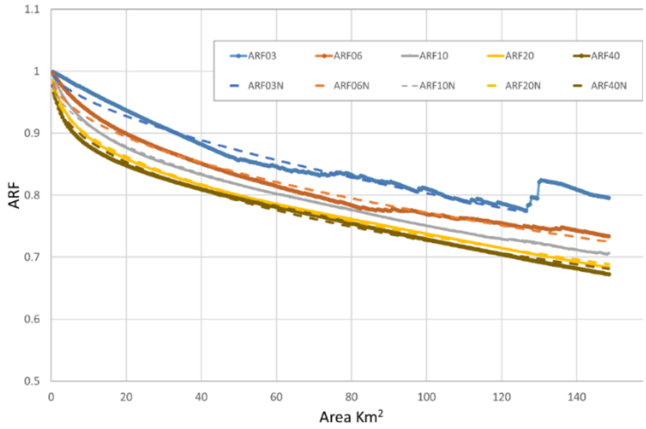

Figure 11. Calculated versus predicted ARF using nonlinear regression-50% percentile

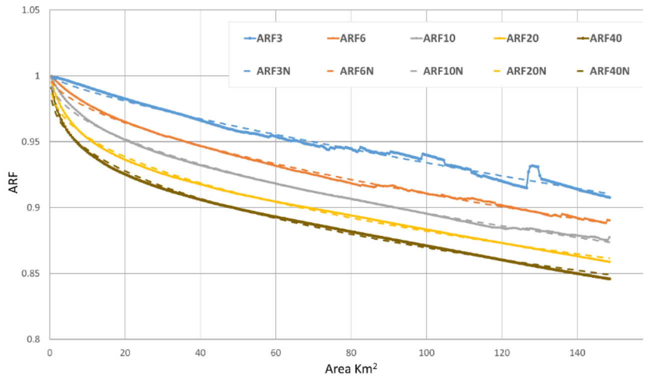

Figure 12. Calculated versus predicted ARF using nonlinear regression-90% percentile

Table 2 Nonlinear regression coefficients and equations-50% percentile

	a	b	Equation	
ARF3	0.522	0.017	$ARF=1 - 0.017 \times Area^{0.522}$	(5)
ARF6	0.476	0.026	$ARF=1 - 0.026 \times Area^{0.476}$	(6)
ARF10	0.449	0.031	$ARF=1 - 0.031 \times Area^{0.449}$	(7)
ARF20	0.407	0.041	$ARF=1 - 0.041 \times Area^{0.407}$	(8)
ARF40	0.388	0.046	$ARF=1 - 0.046 \times Area^{0.388}$	(9)

Table 3 Nonlinear regression coefficients and equations-90% percentile

	a	b	Equation	
ARF3	0.77	0.002	$ARF=1 - 0.002 \times Area^{0.77}$	(10)
ARF6	0.572	0.006	$ARF=1 - 0.006 \times Area^{0.572}$	(11)
ARF10	0.482	0.011	$ARF=1 - 0.011 \times Area^{0.482}$	(12)
ARF20	0.405	0.018	$ARF=1 - 0.018 \times Area^{0.405}$	(13)
ARF40	0.367	0.024	$ARF=1 - 0.024 \times Area^{0.367}$	(14)

V.III. Relation between ARF ratios and average distance between gauges

From all of the above shown figures, one concludes that ARF curves obtained from samples of larger number of stations show less ARF values than those from samples with fewer number of stations. Taking into consideration that the most "accurate" ARF curve is the one resulting from the entire set of rainfall stations, one may search of a way to convert the accurate ARF curve to account for an ARF obtained from a reduced number of stations. Average distance (AVG DIST) between the gauges of each group is calculated and AVG DIST ratio is defined as the ratio between the calculated average distances of a certain group (i.e. ARF3, ARF6, ARF10, or ARF20) and the average distance of the group created with 40 gauges (ARF40). Similarly, ARF ratio is defined as the ratio between the areal reduction factor calculated for a certain area using ARF40 group and the value of the areal reduction factor from other groups (i.e. ARF3, ARF6, ARF10, or ARF20). The relation between both ratios is studied and it is found that a direct strong proportional relation exists between the AVG DIST ratio and ARF ratio as illustrated in Fig 13 below.

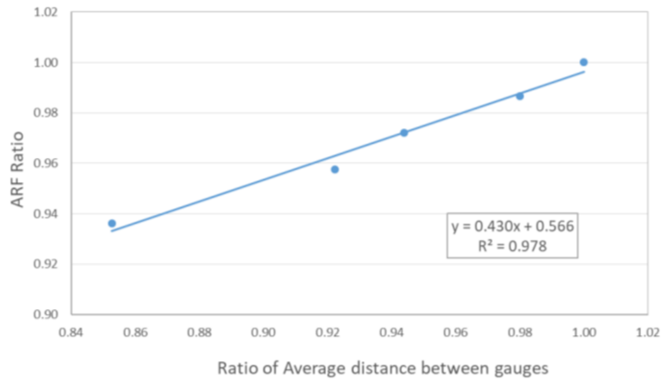

Figure 13 Relation between avg dist. ratio and ARF ratio-90% percentile

Based on the identified relation, it is proved that the different curves of ARF can be related to each other through horizontal shift that represents the difference in average coverage of each gauge in a density group, and a vertical shift which represents the enhancement achieved through increasing the density of gauges used in ARF calculation. Table 4 shows the average distance, average coverage, and the horizontal shift between the ARF curves, while Fig 14 shows the ARF curves when vertically moved down to coincide with ARF40 curve.

Table 4. Gauges average distance and horizontal shifts

Number of gauges in samples	Average Distance R_i (m)	Average Coverage area A_i (Km^2)	Shift A_i-A_{40}
3 Gauges	9500.45	70.35	22.19
6 Gauges	8783.18	58.09	6.53
10 Gauges	8581.60	58.08	6.52
20 Gauges	8266.30	53.64	2.08
40 Gauges	8100.65	51.56	0

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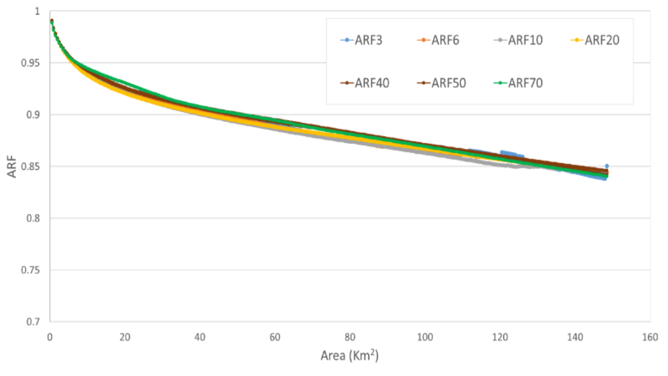

Figure 14: ARF curves after applying horizontal and vertical shifts-90% percentile

V.IV. ARF correction factors Chart

The Proposed ARF correction factor is the factor needed to adjust the areal reduction factor calculated for a certain area in a watershed using few numbers of rainfall gauges through a multiplication factor which is calculated from a dense rainfall gauges network. Table 5 below illustrates the difference between gauges density identified in this study and the corresponding number of gauges while identifying the density of 0.27 gauge/km^2 as an optimum maximum value after which the difference in ARF curves is not noticeable. Fig 15 and Fig 16 illustrates the ARF correction charts which shows the ARF correction factors at different areas for various rainfall gauges densities.

Table 5 Gauges densities

	No. of gauges	Coverage area for one gauge (Km^2)	Gauges density Gauge/Km^2
ARF3	3	50	0.02
ARF6	6	25	0.04
ARF10	10	15	0.07
ARF20	20	7.5	0.13
ARF40	40	3.75	0.27

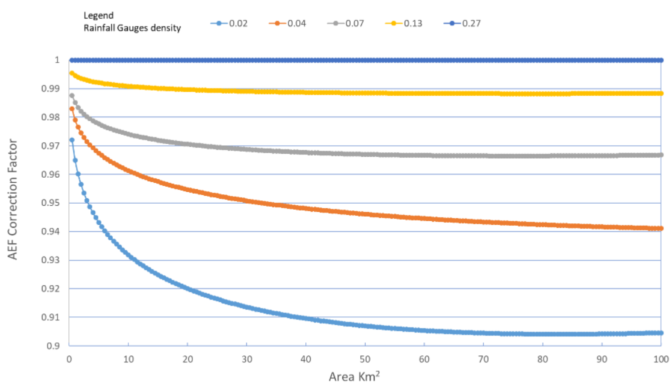

Figure 15 ARF correction factors chart-50% percentile

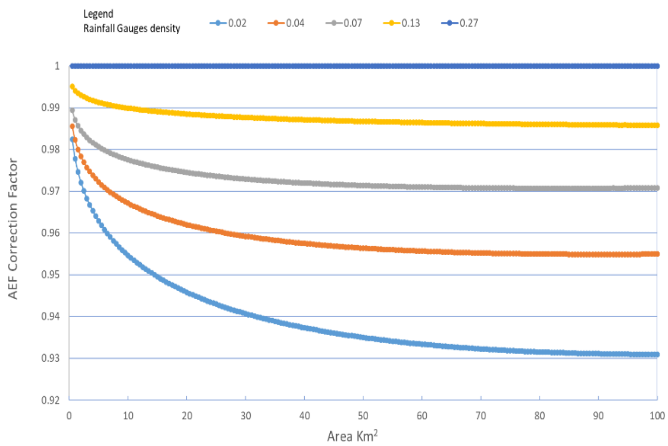

Figure 16: ARF correction factors chart-90% percentile

V.V. VERIFICATION

Two additional groups are made for verification purposes. Groups are made for rainfall densities of 15 and 25 rainfall gauges samples. Each group has 1000 different samples of rainfall gauges obtained using orthogonal sampling. The verification is done to ensure that the obtained results are robust and showing consistency and significance. The acceptance criterion is to estimate the relation between the area and the reduction factor for the selected groups and to check whether it is matching the results for areal reduction factors calculated for the originally selected groups.

The ARF calculations were performed to the verification groups (ARF 15 and ARF 25) and the ARF curves were produced similar to other groups. Results are plotted as shown in Fig 17 hereafter where ARF 15 and ARF 25 curves are fitted in the locations between ARF 10, ARF 20, and ARF 40.

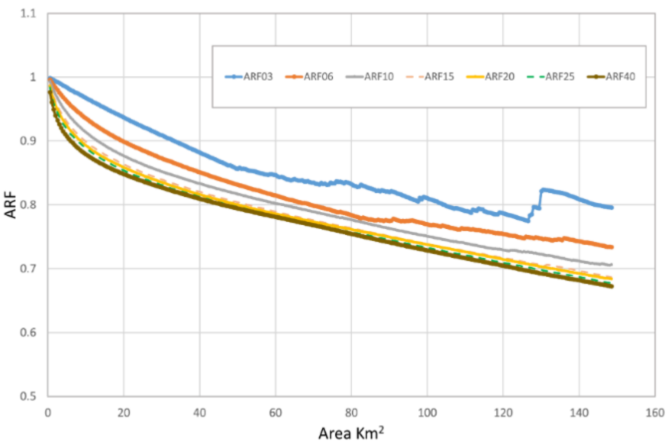

Figure 17. Verification using ARF 15 and ARF 25-50% percentile

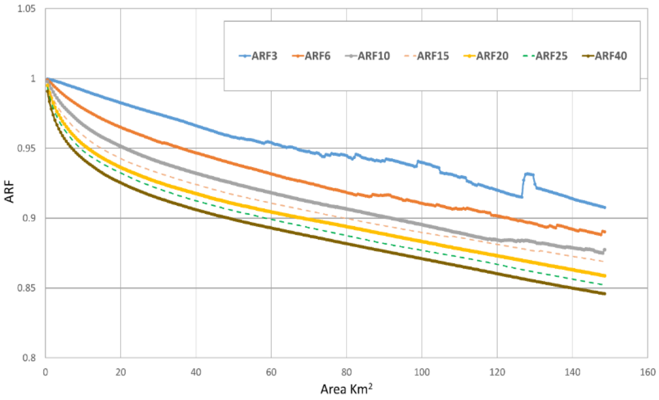

Figure 18 Verification using ARF 15 and ARF 25-90% percentile

VI. CONCLUSION

Based on the research results, the density of ground rainfall gauges (represented as the number of rainfall gauges in 1 square kilometer) affects the value of areal reduction factor. Thus, a correction factor is needed to adjust the value of the areal reduction factor to account for the lack of ground gauges in a certain catchment. In other words, a correction factor to the areal reduction factor should be used for better accuracy of rainfall over a catchment with a relatively large area in which the storm may not cover the whole catchment area. The estimated correction factors will help in correcting the estimated average rainfall on an area by a difference of 0.07 to 0.09 in the absolute ARF values which lead to more accurate design for drainage structures and better water studies.

VII. Acknowledgements

The authors would like to thank engineer Ravish Babna who prepared the GIS tool that was used in this research to calculate the precipitation volume corresponding to a preset depth interval which aided to finalize the numerous numbers of runs required for ARF calculations in an efficient and accurate manner.

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