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COMPARING NETWORK DESIGN APPROACHES IN AREAL RAINFALL ESTIMATE OF NIGERIA RIVER BASINS

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ABSTRACT

This work shows the importance of rain gauge network analysis in the determination of the number of rain gauges that will accurately estimate the mean rainfall of an area. This research therefore looked at the two design approaches viz weighted and non-weighted approaches that will best estimate the number of rain gauges required in a catchment area. From this, it was established that the 87 existing and operating rain gauges in Nigeria is grossly inadequate and hence the need to improve the density to meet World Meteorological Organization (WMO) minimum requirement for the country's geographical location. To do this, the reallocated existing and operating rain gauges is added to the optimum results obtained through the weighted and non-weighted design approaches and hence improve on the existing network density. It is expected that financial considerations may play a role in determining the total number of gauges chosen for the country hence should be determined.

Keywords: rain gauges, weight, non-weight, optimization, network density, stratification.

1. INTRODUCTION

World Meteorological Organisation (WMO, 1965) set standard for minimum number of gauge stations in a network for accurate measurement of rainfall in a catchment. When such standards are not met as in most catchments in Nigeria, the effect is the deficiencies in effectively developing and managing water resources on a scale commensurate with overall level of development (Oyebande, 1990). Apart from this, the deficiency enables gap in information necessary for operation and management of projects in water resources. The foremost consideration in the use of precipitation data is for a proper design of the network of rain gauges in a watershed to collect the data (Mutreja, 1990). The objective of the study is to assess the technical adequacy of the existing rain gauge network in Nigeria. Another is the use of various estimation methods in subdividing the catchment area in substrata and finally optimally relocates the gauges into strata.

According to Rodriquez-Iturbe and Majia (1974), precision in estimating the long-term mean rainfall and total storm depth over an area rainfall information depends on adequate network density design. Wekena (2006) has pointed out that expansion of irrigation development without the knowledge of the water source will have the outcome of agricultural yield reduction and water stress.

The greatest limitation to this study is the general lack of proper record keeping, storage and retrieval system in the country. Although there are several networks such as evaporation, surface water levels, sediment discharge, temperature, groundwater and rainfall, only rainfall network is considered in this study. Though there are several classifications of networks according to Bras and Rodriquez-Iturbe (1976) and Leton and Rodriquez-Iturbe (1977), this study on Nigeria network considers, networks that provide base information for water resource inventory for regional or national planning and background information for the design of more intensive and specific network systems.

2. REVIEW OF LITERATURE

A lot has been published in literature on the need for data collection by hydrologists (Leton and Rodriquez-Iturbe, 1977). Efficient combination of number of gauges required and accuracy of measurement using the network constitute the design of rain gauge network.

2.1 Rain gauge network density

Rain gauges are used in measuring the amount of water that falls over a given watershed or catchment. Using a number of well-planned rain gauges over a catchment constitute the network. The catchment area in square kilometer per the number of gauges gives the network density.

According to Bras *et al* (1976), the density to be used for a particular catchment depends on the economy available and nature of storms. Topography of the catchment also has influence as per Ward (1975) and Nick *et al.,* (1966).

2.2 Estimation of mean rainfall over area

A precipitation gauge measures the rainfall at one geographical point and cannot be representative of the precipitation on a larger area except in its immediate vicinity. The larger the area, greater the error in the assumption, because meteorological conditions may occasionally produce intensities at a point greater than any possible combination of circumstances could produce over an area greater than a few hectares (Mutreja, 1990).

Point estimates are combined by such methods as Thiessen polygon, Isohyetal (Akin, 1971), Pande *et al* (1978), Raughunath (1986), block kriging method (Cheng *et al,* 2011) etc. to give the mean areal rainfall or storm depth over an area.

2.3 Errors in rainfall measurement

Rodda (1967) has observed that notwithstanding the progress made in rainfall measurement, advancement in technology, rainfall measurement results are still marginally near to the solution or the true value. The difference between the measured and true rainfall is attributed to measurement errors. These errors are broadly classified into systematic such as siting, exposure, wind effect and random errors which include observational mistakes, variation of rainfall, microclimatic irregularity etc. according to Mooley *et al* (1981).

2.4 Approaches to network design

Several approaches are adopted to achieve adequate density with high precision and they include:

a) Weighted approach to network design

Leton and Rodriquez-Iturbe (1977) has argued that weighting point rainfall reading is meant to obtain reliable representative mean value free from factors such as infiltration. At optimum weights, minimum error of estimation is obtained. Gandin (1970) applied weighting ratios to discrete meteorological elements from which the mean square error is obtained. Mooley and Ismail (1981) have applied this approach in the design of Vidiarbha region network in India. Rainfall was estimated by discrete summation after weighting the point rainfall. The difference between the discrete summation and the true areal mean of the process gives the mean square error.

$$MSE = E\left(\sum_{j=1}^{n} w_i R_j' - \frac{1}{A}\iint_A R'dxdy\right)^2 \quad (1)$$

Where E is the expected value, w_i is the weight, R_j' is the deviation of point rainfall from its normal.

Shih (1982) improved accuracy in mean estimation and rain gauge density by use of tolerable errors error method. In this method, covariance factor is used to compute variances viz: relative variance, which depend on number of gauges and spatial variance, which is independent of the number of gauges were used to estimate the mean rainfall.

The mean areal rainfall is established using one of these: 1) Random Sample, 2) Stratified Sample without optimum allocation of gauges to stratum and 3) Stratified Sample method with optimum allocation of gauges to stratum. The square root of the relative variance obtained using the three sample method listed above gives their relative standard error.

Since spatial variation for both stratified with and without optimum allocation is the same, spatial variance is determined using either random sampling method or stratified sampling methods. Weighting is done using either special stratum weighted ratio, used for relocation of rain gauges to data or the weight of each stratum, that is, ratio of stratum area to the total catchment area

$$\left(\frac{A_i}{A}\right) \quad (2)$$

b) Non weighted approach

Non weighted approach relates number of gauges to either variance of the rainfall, coefficient of variation, correlation coefficient between stations or errors of estimation.

Sutcliffe (1966) gave one of such relations using standard error of mean (SEM) and the variance (S) of the N data as

$$SEM = \left({S^2}/{N}\right)^{\frac{1}{2}} \quad (3)$$

Also given a precision, say, e, the required number of gauges (N_r) is estimated using Herbst and Shaw (1969) formula as

$$\frac{e}{RSE} = \left({N_u}/{N_r}\right)^{\frac{1}{2}} \quad (4)$$

Where, N_u *is* the existing number of gauges and RSE is the reduced standard error.

Raughunath (1986) reported a simple approach that relates the number of gauges to the coefficient of variation and error to be tolerated as in

$$N = \left({C_v}/{e}\right)^2 \quad (5)$$

This approach is observed to be insensitive to the distribution of the gauges and the catchment area even though it is simple.

Another non-weghted approach by McCullich in Mutreja (1990) employed the idea that for monthly totals recorded in a network of gauges that were fairly uniformly distributed, the coefficient of variation of the mean for each month (${C_v}/{C'}$) is used to determine the adequacy of the network.

$$N = \left({C'}/{10}\right)^2 n \quad (6)$$

For this system, if C' is 10 or less, then the number of gauges in the network is considered adequate. If C' is more than 10, the number of gauges required can be calculated using equation (6) above.

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3. MATERIALS AND METHOD

The data used for this study is the monthly rainfall data for existing networks collected from the Nigeria Meteorological Agency Lagos and various River Basin Development Authorities in the country. The 10years climate data is therefore from several gauge stations spread all over the country

Network design is carried out in stages. The first stage involves stratification and placement of gauge stations. Thereafter covariance factor among gauge stations is computed. From the result of covariance factor, relative and spatial variances is computed using random sample method, stratified method with optimum allocation and stratified sample without optimum allocation of gauges (Shih 1982). For the stratification, Pande *et al* (1978) method of weighting is used.

A relative variance computation from the covariance between stations is obtained and used to estimate the percentage standard error, which would be used to establish a relation with mean rainfall as suggested by Jackson (1969).

3.1 Theory of analysis

The mean rainfall for a whole zone is computed with

$$R = a_1R_1 + a_2R + \dots\dots\dots\dots\dots\dots\dots + a_{2n}R_n = \sum_{i=1}^{m} a_iR_i \qquad (7)$$

Where a_i is the weighting ratio or ratio of stratum area to the area of the catchment.

According to Obi (1991), the covariance between two rain gauge stations i and j having n variate rainfall is given by

$$C_{ov}(R_i\,,R_j) = \frac{1}{n}\sum_{i=1}^{n}(R_i - \bar{x})(R_j - \bar{y}) \qquad (8)$$

Where R_i and $R_j$are the rainfall at stations I and j respectively, while x and y represent the mean rainfalls at stations I and j, respectively.

The average variance for a station within a stratum is given by Shih (1982) as

$$S_{oi} = \frac{1}{N_i}\sum_{k=1}^{Ni} var\bar{R}_{ki} \qquad (9)$$

The total variance determined by random sample method is given as

$$S^2(\bar{R}) = \frac{1}{N}(S_o^2 - \sigma_{okl}) + \sigma_{oki} \qquad (10)$$

According to Shih (1982) the spatial variance for random sample method is given by

$$S_o^2(\bar{R}) = \sigma_{okl} \qquad (11)$$

However, the spatial variance for both stratified with and stratified without optimum allocation is given as

$$S_o^2(\bar{R}) = \sum_{i=1}^{n} a_i^2\sigma_{okli} + 2\sum_{i=1}^{n}\sum_{j=1,i>j}^{n} a_ia_j\sigma_{oklij} \qquad (12)$$

4. RESULTS AND DISCUSSIONS

Tanko (1996) has observed that rainfall being a random hydrological event both in time and space needs adequate rain gauge network for accurate measurement. Ciscerrova and Hutchinson (1974), however, looked at adequate network for accurate for rainfall estimation from best selection of rain gauge numbers and placement of same to minimize tolerable error within a given catchment.

Analysis and design of network in this work therefore involves the use of both weighted and non-weighted approach to estimate number of rain gauges required per catchment area and comparing results (Ngene, 2009). The process starts with division of the country into 12 River Basins as seen in Figure-1 below.

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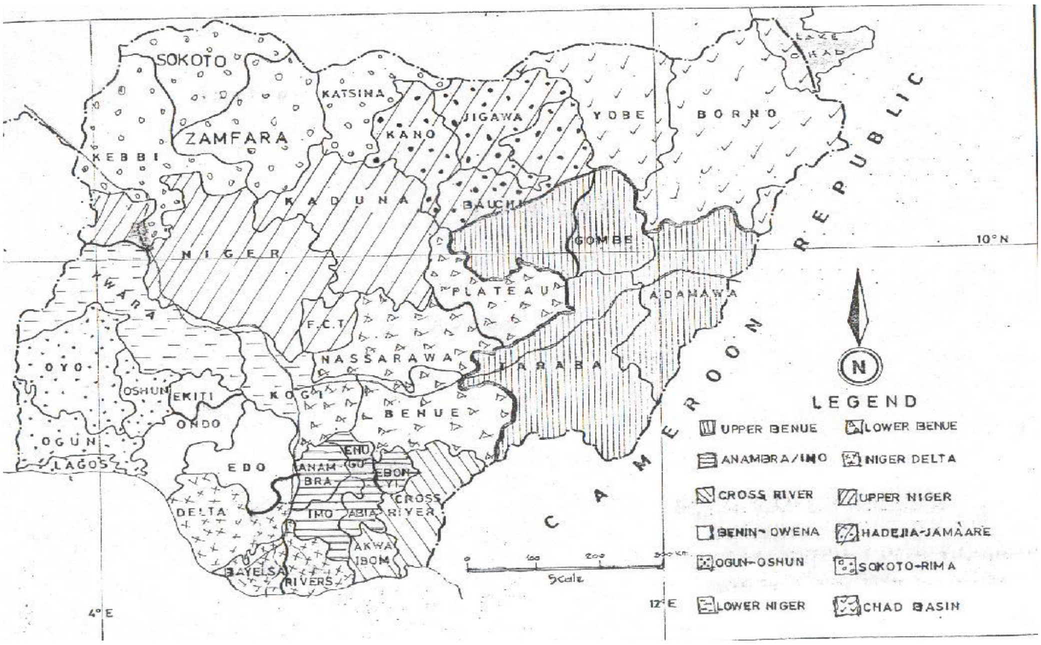

Figure-1. Map of Nigeria - location of river basins.

Each River Basin is further stratified according to the number of existing rain gauge stations as per Figure-2.

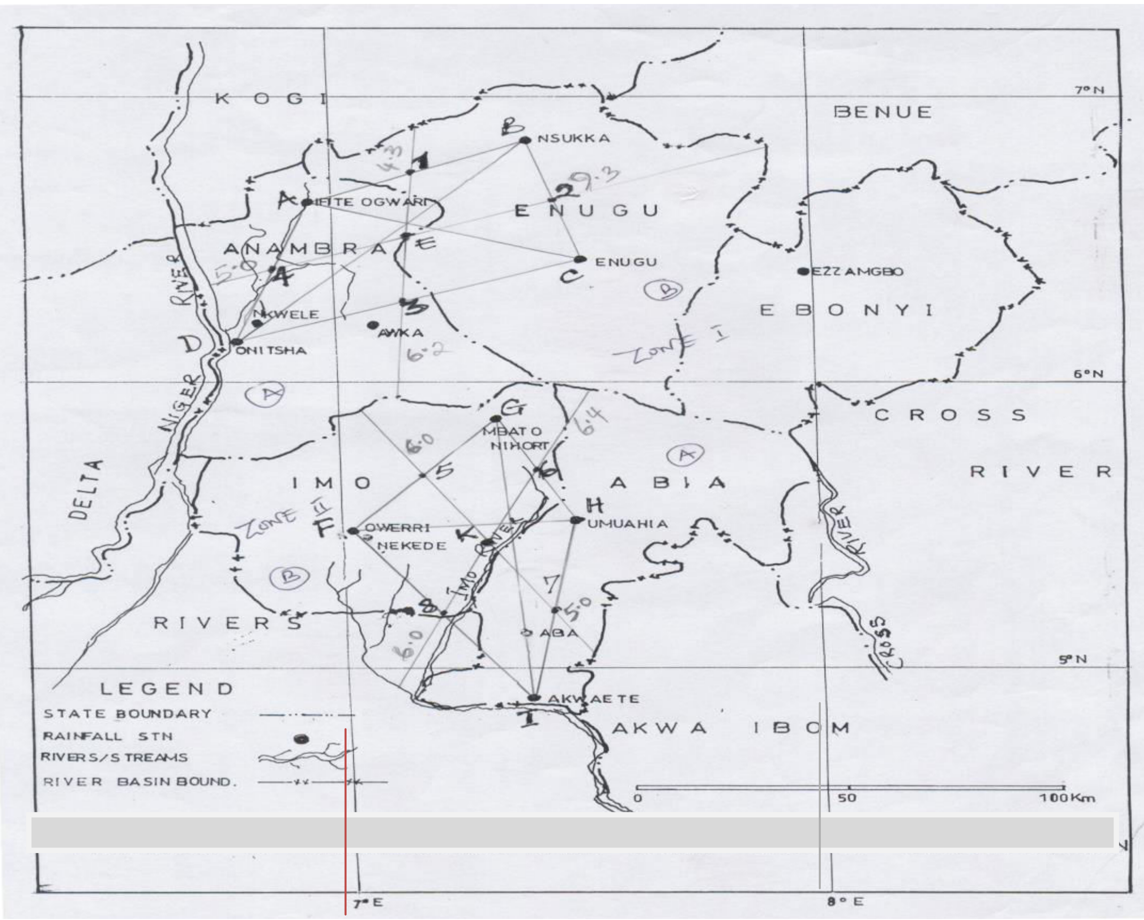

Figure-2. Stratification of Anambra/Imo river basin.

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Table-1 below indicates the different zones, strata and weights obtained for Anambra/Imo River Basin and this format represents the approach used for all the other River Basins in the country.

Table-1. Anambra/Imo river basin stratification and station weights.

S/N	Zone	Strata	Stations	Weight
1	I	A	Ifete-Ogwari	0.145
			Onitsha	0.205
2		B	Nsukka	0.269
			Enugu	0.381
3	II	A	Mbato-Nihort	0.282
			Umuahia	0.235
4		B	Owerri	0.264
			Akwaete	0.220

Using the rainfall data per station and collected per River Basin, the variance and covariance matrix of annual rainfall for each station in a River Basin is computed as shown in Table-2 below for Anambra/Imo River Basin. The River Basin has two zones and each zone is further subdivided into strata A and B as indicated in the Table.

Table-2.

	Umuahia (Umudike)	**Mbato-Nihort**	**Owerri**	**Akwaette**	**Ifite Ogwari**	**Onitsha**	**UNN - Nsukka**	**Enugu Met**
Umuahia (Umudike)	128326.94	74558.80	34131.55	26880.82	75150.30	29968.52	45861.22	57702.58
Mbato-Nihort		250988.72	53328.91	-5731.60	71404.07	45851.47	24020.84	86286.42
Owerri			82208.97	22587.24	66977.47	47922.70	20538.62	57540.84
Akwaette				83173.98	21944.49	16732.30	34736.67	48064.08
Ifite Ogwari					217027.88	49459.46	35657.72	92610.30
Onitsha						45157.17	12621.91	44477.50
UNN - Nsukka							61658.22	49277.65
Enugu Met								101487.28

The covariance between strata for annual rainfall is computed and shown on table 3 below.

Table-3. Covariance between Strata for Annual Rainfall (mm^2) for Anambra/Imo River Basin.

ZONE	STRATA	A	B
1	A		46341.86
	B		
2	A		27152.42
	B		

Another Table-4 shows for each stratum, the Area ratio (a_i), Number of stations(N_i), Annual mean rainfall$(\bar{R})$, Variance(σ^2), Covariance(σ), for stratum and stratum weighted ratio(C_i) per zone.

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Table-4. Area ratio (a_i), Number of stations(N_i), Annual mean rainfall$(\bar{R})$, Variance(σ^2), Covariance (σ), for stratum and stratum weighted ratio(C_i) for Anambra/Imo River Basin.

Zone	Stratum	a_i	N_i	$\bar{R}$	σ^2	σ	C_i
1	**A**	**0.350**	**2**	**529.67**	**131093**	**49459**	**0.461**
	B	0.650	2	997.00	81573	49278	0.539
Mean			4	763.34	106333	49369	
2	A	0.455	2	968.87	105750	26881	0.410
	B	0.545	2	1124.84	166599	53329	0.590
Mean			4	1046.86	136175	40105	

Using the results obtained in the foregoing analysis, the allocation of rain gauges per zone is made as shown in Table-5 below.

Table-5. Allocation of rain gauges.

Zone	Stratum	N	C_i	N_i=NC_i	Required rain gauge
1	A	4	0.461	1.84	2
	B		0.539	2.16	2
2	A	4	0.410	1.64	2
	B		0.590	2.36	2

All these results summarized the weighted approach to network design for Anambra/Imo River Basin while the comprehensive result shown in Table-6 below indicates the allocation of rain gauges for all the River Basins in Nigeria.

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Table-6. Reallocation of rain gauges using special stratum weighted ratio for the various river basins.

S/N	River basin	Number of existing gauges per basin	Stratum	Zone I		Zone II		Zone III	
				Existing gauge	Required gauge	Existing gauge	Required gauge	Existing gauge	Required gauge
1	Anambra/Imo	8	A	2	2	2	2	-	-
			B	2	2	2	2	-	-
2	Benin-Owena	4	A	2	1	-	-	-	-
			B	2	3	-	-	-	-
3	Chad	5	A	3	3	-	-	-	-
			B	2	2	-	-	-	-
4	Cross River	4	A	2	3	-	-	-	-
			B	2	1	-	-	-	-
5	Hadejia-Jaamare	5	A	3	3	-	-	-	-
			B	2	2	-	-	-	-
6	Lower Benue	6	A	4	3	-	-	-	-
			B	2	3	-	-	-	-
7	Lower Niger	5	A	3	5	-	-	-	-
			B	2	0	-	-	-	-
8	Niger Delta	4	A	2	1	-	-	-	-
			B	2	3	-	-	-	-
9	Ogun-Oshun	8	A	3	3	-	-	-	-
			B	3	3	-	-	-	-
			C	2	2	-	-	-	-
10	Sokoto-Rima	4	A	2	1	-	-	-	-
			B	2	3	-	-	-	-
11	Upper Benue	17	A	2	3	3	3	2	2
			B	3	2	2	2	3	4
			C	-	-	-	-	2	1
12	Upper Niger	17	A	3	4	3	2	3	2
			B	3	2	3	4	2	3

The non-weighted approach is computed at defined statistical accuracy, confidence level and tolerable error as shown in Table-7 below.

Table-7. Optimum number of gauges at statistical accuracy for Anambra/Imo river basin.

	Statistical accuracy	Value of tά	Zone I	Zone II	Zone (I + II)
			No of gauges reqd.	No of gauges reqd.	Optimum design
Confidence level	80%	1.638	7	6	13
	90%	2.353	9	8	17
	95%	3.182	11	10	21
Tolerable error	10%	1/10	26	16	42
	15%	3/20	12	7	19

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The above Table is for Anambra/Imo River Basin, the test case, while the comprehensive result for all the River Basins in Nigeria is shown in Table-8 below.

Table-8. Comparison of results for network improvement of each of the river basins.

S/N	River basin	Number of existing guages	Confidence level	Network density improvement		
				Optimum value	Design value at tolerable error	
					10 %	15 %
1	Anambra/Imo	8	80%	13	41	18
			90%	17	86	38
			95%	20	157	70
2	Benin-Owena	4	80%	4	34	15
			90%	5	70	31
			95%	7	128	57
3	Chad	5	80%	5	37	17
			90%	6	72	32
			95%	8	123	55
4	Cross River	4	80%	6	10	5
			90%	8	21	10
			95%	10	39	17
5	Hadejia-Jaamare	5	80%	6	29	13
			90%	7	55	25
			95%	8	94	42
6	Lower Benue	6	80%	6	32	14
			90%	8	60	27
			95%	9	98	44
7	Lower Niger	5	80%	7	13	6
			90%	9	26	11
			95%	11	44	19
8	Niger Delta	4	80%	3	140	62
			90%	3	289	128
			95%	4	528	235
9	Ogun-Oshun	8	80%	7	46	21
			90%	9	83	37
			95%	10	129	57
10	Sokoto-Rima	4	80%	5	24	11
			90%	6	49	22
			95%	8	90	40
11	Upper Benue	17	80%	26	116	52
			90%	32	220	98
			95%	37	364	162
12	Upper Niger	17	80%	32	61	27
			90%	39	114	51
			95%	46	188	83
		87				

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5. CONCLUSIONS AND RECOMMENDATIONS

It has been shown from this study that Nigeria currently has about 87 existing and operating rain gauge stations. This number for land masses of 923300Km^2 gives a gauge network density of 10613 Km^2/Gauge. The World Meteorological organization (1965) determined that the minimum gauge density for Temperate Mediterranean and Tropical zone flat area to be between 600-900 Km^2/Gauge. This wide difference highlights the gross inadequacy of the rain gauge network of Nigeria, hence the need to improve on the Numbers.

From Table-8, it is shown that the existing number of gauges for all the 12 River Basins is lower than the optimum values at between 80-95% confidence levels. To improve network densities, the design value at acceptable tolerable error and the optimum values are added together. The choice of optimum value that will improve the network density will however consider the cost of establishing and running a network of rain gauges also and not just the accuracy of mean rainfall obtained.

Therefore to design the network to accommodate the minimum gauge density stated above, both weighted and non-weighted approach is required. The weighted approach is used to reallocate the existing rain gauge for optimum use. The non-weighted approach using acceptable statistical analysis at certain confidence level and tolerable error, however, optimizes the number of rain gauge for the whole country. It is important to note that the final optimal values of rain gauges can be allocated using the weighted approach to ensure good spread and hence better accuracy of areal rainfall mean in Nigeria.

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