Sustainable development, climate variability and data limitation in flood management

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Abstract

As the influence of climate change on flooding becomes more evident, the assumption of stationarity in flood frequency estimation is no longer valid for flood planning, management and infrastructural development. To alleviate climate driven flood effect on citizens and achieve sustainable development goals, ground monitoring stations are established to collect long-term river measurements used in managing flooding. In situations where data is limited or unavailable as often the case in developing regions due to administrative, financial or technical discrepancies, an alternative method such as regional flood frequency analysis is adopted to salvage the situation by leveraging data from gauge stations at close proximity to the area of interest defined by hydrologically similar properties. In this study we explore the use of freely available ICIWaRM Regional Analysis of Frequency Tool (ICI-RAFT) to tackle the challenge of data sparsity and climate variability effect on flood frequency and magnitudes. Climate index embedded in ICI-RAFT is correlated to annual maximum floods and applied to account for the effect of time varying climate on regional and single-site flood magnitudes. Madden-Julian Oscillation (MJO) was identified to have the highest influence on flood estimates, with evidence of the difference between stationary and non-stationary flood quantiles shown in a comparative display. The results assert the importance of taking climate variability into cognizance in flood frequency estimation, and the need to review flood management measure based on the assumption of stationarity.

Keywords: Climate change, sustainable development, Regional flood frequency, Climate Index

1. Introduction

The impact of flood disaster has been on the rise globally, owing to climate change that results in irregular weather patterns and affecting all aspects of the hydrological cycle including evaporation, precipitation, rainfall runoff and discharge, resulting in more frequent and intense flooding. With this trend on the rise as global mean surface temperature increases to the warmest ever (Hansen et al., 2016), effective flood management is needed to curtail flood menace now and in the future, starting with the estimation of flood magnitude and probability of occurrence that builds from historical data (Komi et al., 2016). The availability of data to estimate flood magnitudes has however been a reoccurring challenge in developing countries, and this issue in Nigeria spans from the 1980s (Maxwell, 2013). These challenges have been attributed to inconsistencies associated with data collection and management. detailed deteriorating condition of gauge stations, personnel incompetence, security and mobility challenges as some of the core causes of data sparsity, while argued that financial limitations and technical know-how were the fundamental causes of ineffective data management, resulting in incomplete, inaccurate, fabricated and obsolete data. Even when data is available, storage in paper formats limits accessibility and applicability for informed decision making.

Climate driven flood disasters compromise the ability to accomplish specific suitable development goals, essentially affecting people living in vulnerable locations, impacting the livelihood and socio-economic activities, disrupting infrastructure, destroying agricultural produce, 2009), impacting health adversely and the loss of lives. The sustainable development goals directly affected by climate induced flood include (I) Poverty elimination, (II) Food security, sustainable agriculture and hunger elimination, (III) quality education and learning opportunities, (IV) sustainable water management, (V) reliable, affordable and sustainable energy, (VI) sustainable economic growth, (VII) infrastructural resilience and industrialization, (VIII) safe, resilient and sustainable settlements (IX) climate change combat and impact reduction, and (X) aquatic resources conservation and sustainable use.

Considering that sustainable development is focused on development that meets the needs of today without compromising the chances of the future generation's ability to meet their needs, this study focuses on overcoming the challenge of data limitation and takes into cognizance climate variability effect on future floods by the application of a regional flood frequency estimation approach in Western Nigeria.

The dearth of hydro-meteorological data in Nigeria has been widely documented, as sparsity of measuring stations in Nigeria that leaves several catchments ungauged. Contrary to the World Meteorological Organization hydrological network density recommendations of 384 and rain gauge density optimization suggestion of 970, only 237 hydrological and 291 rain gauge stations exist across Nigeria. Hydro-meteorological data is essentially applied in forecasting expected flood events based on past trends. The length of past data contributes to the uncertainty in derived estimates, as longer length of data results in more accurate forecast. Review of river and rainfall forecasting models (Figure 1) show that rainfall data are generally longer than river discharge directly applied in flood frequency estimation needed for flood management and hydraulic structure design.

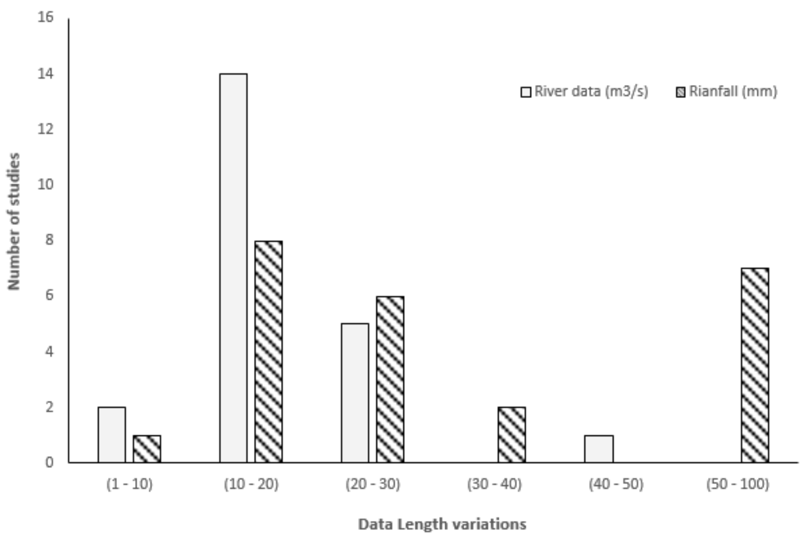

Figure 1 Review of data length rainfall and River discharge research in Nigeria

Flood frequency estimation requires fitting annual maximum time series to a predefined or best fit probability distribution function such as Generalized Extreme Value (GEV), Generalized Pareto (GP), Pearson Type III (PE3), Generalized Normal(GNO) and Generalized Logistic (GLO) when adequate data is available. Contrastingly, data limitation causes hydrologists and engineers to explore alternative approaches that integrate data from various stations at close proximity to the area of interest with remote sensing derived catchment properties to create a regional flood estimate.

Remote sensing (RS) in past three decades has played a crucial role in water resource management globally and Nigeria in particular. Remote sensing allows for the collection of data without being in direct contact with the object under investigation, and with the challenge of accessing flooded region(s) due to road infrastructure disruption, the importance of remote sensing cannot be overemphasized. The spatial-temporal capacity of remote sensing, ease of manipulation of digital data and the peculiar advantage of radar sensor to capture cloud free day and night time images enhances inundation mapping. Despite these advantages, RS is not without limitations, as time lapse between satellite image captures, high cost associated with acquisition of high resolution imagery, cloud cover, vegetation canopy and rugged terrains, have been reported in several instances to hamper RS application, resulting in uncertain results. However, the advantages of RS significantly outweigh the disadvantages and recent advancements have led to the advent of open source remote sensing.

Satellite data applicable in flood management include optical and radar imagery, digital elevation models (DEMs), and altimetry, useful in flood mapping, hydrological modelling, hydraulic modelling, and serves as supplementary data for model calibration, validating and accuracy assessment. A review of 100 papers on flood research in Nigeria shows the range of data applied in flood management studies (Figure 2), presenting a high reliance on open source and low cost remote sensing.

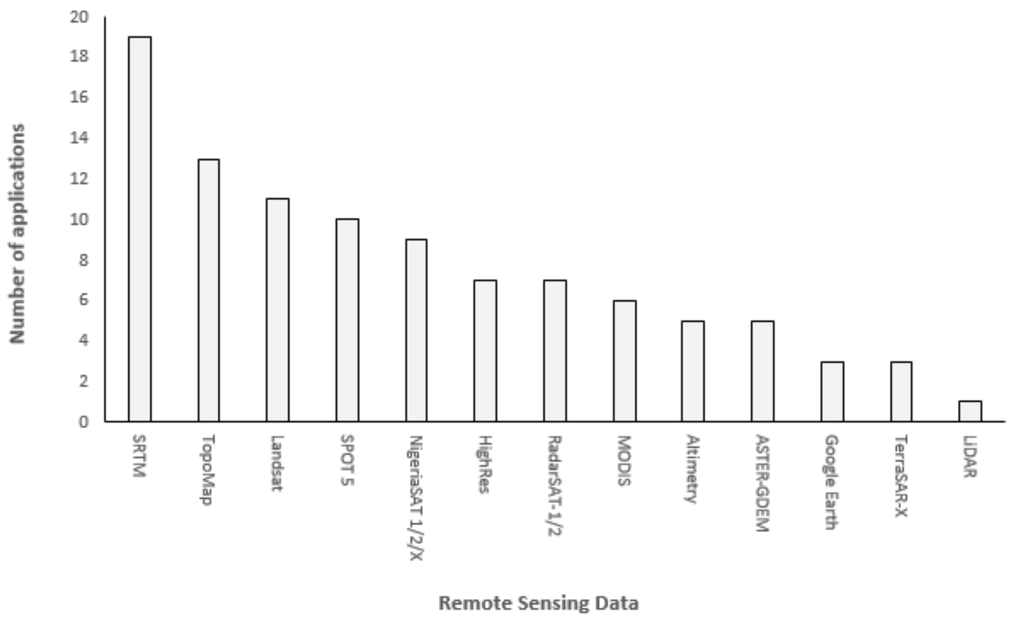

Figure 2 Remote sensing data application in Nigerian Flood Management

2. Study Area and Data availability

The Ogun-Oshun river basin (Figure 3) is located between $6^{o}25^{'}$ – $9^{o}25^{'}$N latitude and $2^{o}70^{'}$ – $5^{o}10^{'}$E Longitude, bordered in the west by Ouémé River Basin, Benin Republic, east by Benin-Owena river basin, north by Lower Niger river basin and south by the Atlantic Ocean. The Ogun-Oshun river basin encompasses Ogun, Oyo, Osun and Lagos states within a 56 000km^{2} area, with major rivers including Ogun and Osun, and tributaries comprising of Yewa, Sasa, Omi, Ofiki, Ibu, Ona, Oba and Omi discharging into the Lagos Lagoon and Atlantic Ocean.

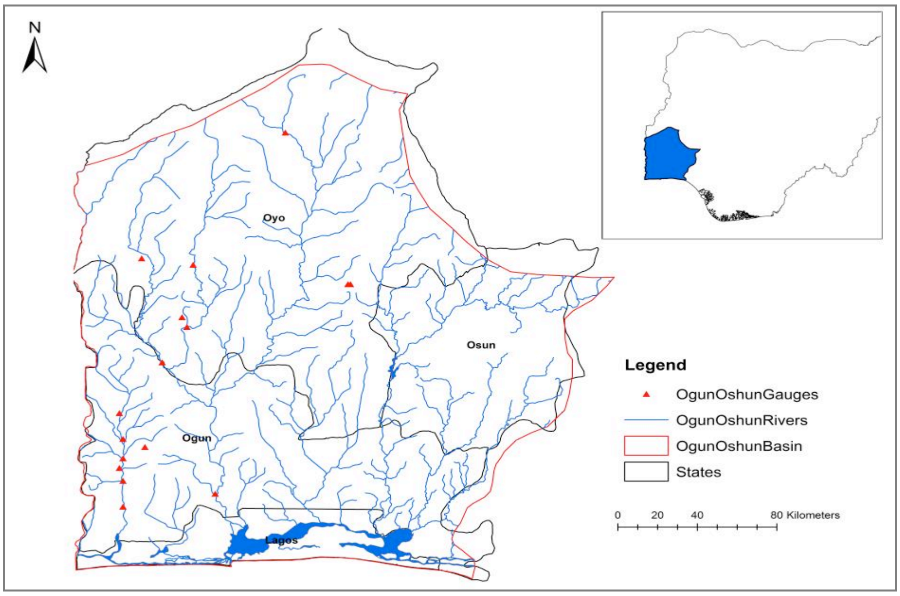

Figure 3 Ogun-Oshun River basin, Area of Interest

The area is characterised by a hydrology defined by an annual rainfall ranging from 1400 to 1500 (mm), mean annual temperature ranging from 25.7^{o}C (in July) to 30.2^{o}C (In February), humidity varying from 37 – 54% in February and 78 – 85% between June and September. Also the region being located within the tropical rainy climate is influenced by tropical continental (cT) and tropical maritime (mT) air masses responsible for the southwest and northeast winds respectively, that creates the Intertropical Convergence Zone (ITCZ) which results in seasonal pressure belts and isotherm shifts and climate variability. Climate varying conditions have been reported to be the cause of intense short duration rainfall that consequently result in flooding within the Ogun-Oshun river basin.

The data used in this study was acquired from the Ogun – Oshun river basin (OORB) and other literature including, and is presented in Table 1. Catchment areas were derived from Shuttle Radar Topography Mission (SRTM) digital elevation model. AMS data from 17 gauge stations was used in this study, with data points varying from 14 to 29 from the years 1966 to 2012.

3. Methodology

Typically, most hydrologic flood frequency studies are based on the assumption of homogeneity, implying that climate and environmental conditions do not change over time. However, with evidence of climate change manifesting in the past decades and its effect on precipitation and resultant run-off and discharge, this assumption is obsolete and Non-stationary flood frequency is advised to capture this variability. In this study ICIWaRM Regional Analysis of Frequency Tool (ICI-RAFT) is employed, a freely available software that enables L-Moment regional flood frequency implementation while accounting for climate variability by integrating a range of climate index provided by the National Oceanographic and Atmospheric Administration (NOAA). Prior to L-moment reginal flood frequency implementation, preliminary data analyses are undertaken to augment missing data using multiple imputation, identify outliers, detect trends, test for homogeneity and serial correlation.

4. Results and Discussion

Data preparation results are presented in Table 1, highlighting filed missing data, identified outliers, trends, homogeneity and serial correlation within the dataset. P-values are used to denote the significance of outliers, trends, and data homogeneity, with $P < 0.05$ indicating strong significance.

Serial correlation on the other hand is stipulated to range from -1 to 1, indicating strong non-correlation and correlation respectively. Low lying outliers were largely discordant from the time series, and thus were treated as missing values, while high outliers were consistent with recorded flood events. Four significantly trended and heterogeneous site including Ijaka-Oke, Ofikki-Igana, Ofiki/Iganna-Ilere road and Oba/Oyo-Obgomoso were identified and the time series of trends and break-point analysis plots are presented in Figure 4. The highest level of correlation between climate index and annual maximum series was observed to be linked to the Madden-Julian Oscillation (MJO). The correlation coefficients based on MJO were Ijaka-Oke = 0.27, Ofikki-Igana = 0.42, Ofiki/Iganna-Ilere road =0.31 and Oba/Oyo-Obgomoso = 0.45.

Table 1 Preliminary test results

S/N	Station ID	N	Missing	Outlier	Trend	(+/-)	Homogeneity	Lag1 correlation
1	Ijaka-Oke	33	6	0.464	0.001	+	0.081	0.516
2	Eggua	33	7	0.017	0.721	+	0.149	0.083
3	Ebute Igboro	33	8	0.005	0.420	+	0.193	0.083
4	Idogo	33	9	0.001	0.768	+	0.776	0.330
5	Ajilete	33	4	0.016	0.457	-	0.290	-0.025
6	Yewa Mata	14	0	0.049	0.518	-	0.885	-0.209
7	Oyan/Ilaji-Ile	26	0	0.838	0.000	-	0.548	0.319
8	Ona river	18	0	0.955	0.654	-	0.439	0.019
9	Oshun/Iwo railway	24	0	0.061	0.132	+	0.189	0.305
10	Oba/Oyo-Obgbomoso	23	0	0.298	0.016	+	0.0013	0.272
11	Ofiki/Ofiki town	23	1	0.128	0.566	+	0.6594	-0.254
12	Ofiki/Iganna-Ilere road	23	0	0.370	0.057	+	0.0133	0.302
13	Ofiki/Igangan	23	0	0.398	0.057	+	0.0472	0.274
14	Ogun/Shepeteri	23	0	0.079	0.172	+	0.1838	-0.164
15	Ogun/Oyo-Iseyin road	23	0	0.312	0.566	+	0.4437	0.125
16	Ogun/Ibaragun	24	0	0.279	0.472	+	0.463	-0.018
17	Ogun/Olokemeji	22	0	0.000	0.617	-	0.170	0.077

Trend-direction (+/-), Outlier, Trend and Homogeneity depicted by p-values, Lag1 correlation varies from -1 to 1

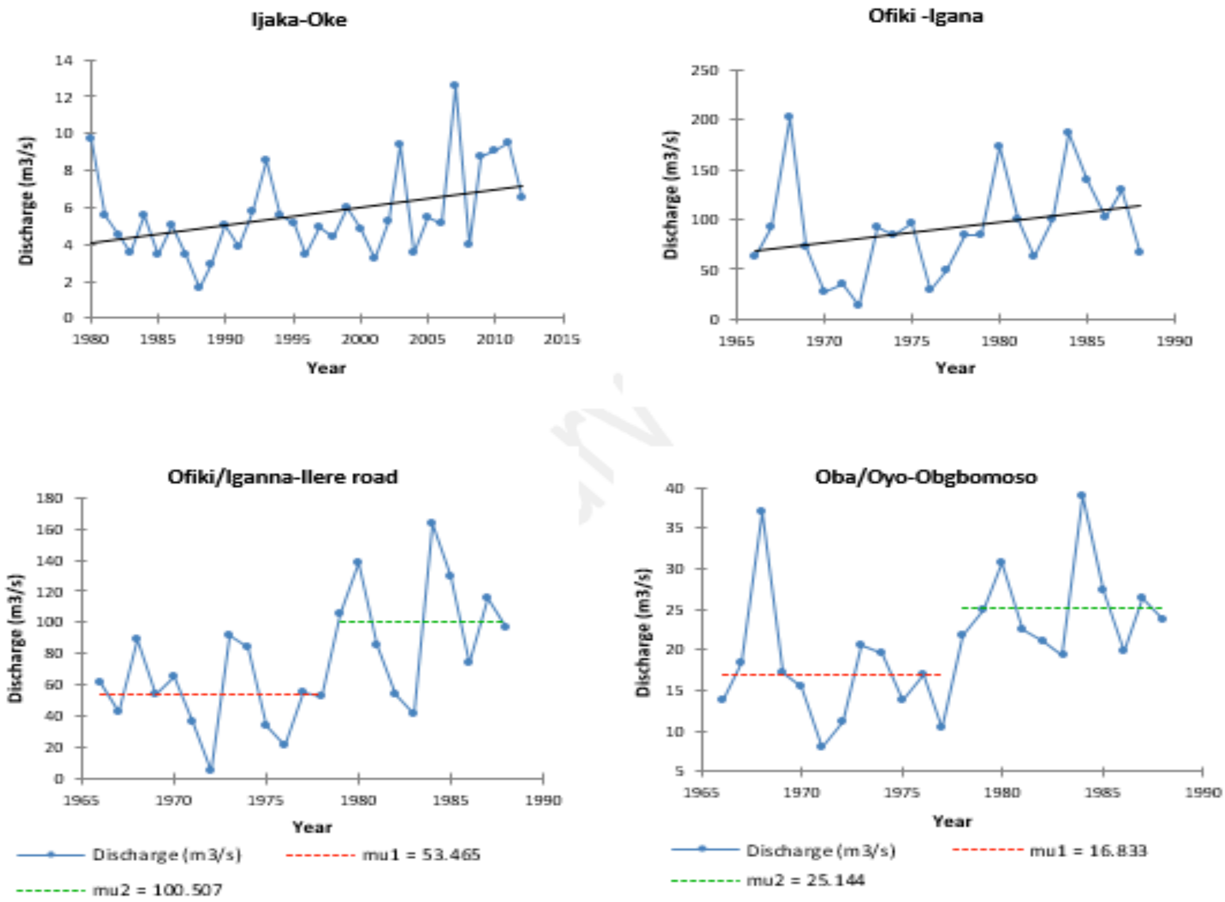

Figure 4 Trend display and break points in Non-Stationary data stations

Results capturing the effect of climate indices inclusion are presented in **Error! Reference source not found.** for identified homogenous sites. Evidence of climate variability impact on quantile estimates increases with increasing return periods, thus proving the time dependency of the covariate function. Also, sites with high climate indices annual flood times series correlation showed reduced difference in flood frequency estimates at each return period. For the four comparative stations, contrasting levels of quantile estimates were recorded, Ofiki/Igangan-Ilere road and Oba/Oyo-Obgbomoso stationary and non-stationary flood magnitudes were higher than direct (single-site) flood magnitudes, different from Ijaka-Oke were stationary regional and single-site flood estimates are higher non-stationary regional and at Ofiki-Igangan stationary non-regional and direct flood quantile estimates were higher than those of stationary regional.

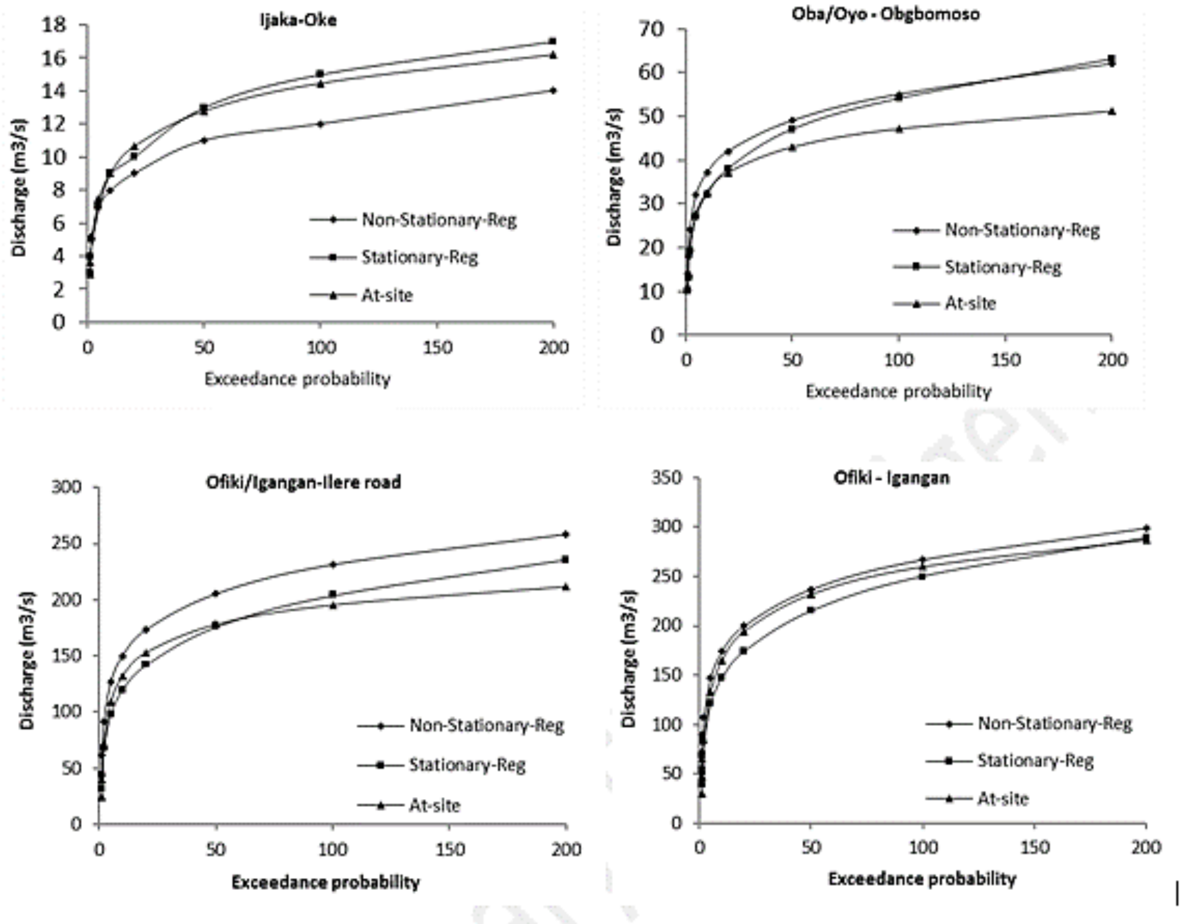

Figure 5 Probability plots of Stationary, Non-stationary regional and At-site flood frequency analysis

5. Conclusion

The use of climate index embedded in freely available ICIWaRM Regional Analysis of Frequency Tool (ICI-RAFT) software was explored in this study to assess climate variability effect on non-stationary flood quantile in the sparsely gauged region of Western Nigeria. Thus ensuring future changes in climate is taken into account to ensure sustainable flood management approach deployment and reduce impact on the populace. 17 gauges in the Ogun-Oshun basin were analysed to develop a region flood quantile used in estimating flood magnitudes within the sparsely gauged river. The results show the relevance of incorporating non-stationarity in flood frequency estimation, the value of remote sensing in supporting flood management in developing regions. Therefore, the need for review in flood analysis standards is advice to ensure improved flood management planning and implementation.

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