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Incorporation of non-stationarity in precipitation intensity-duration-frequency curves for Kerala, India

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Abstract. Intensity-Duration-Frequency (IDF) curve is an essential hydrologic tool used for the design of hydraulic infrastructure. In a changing climate scenario, the assumption of a static return period of precipitation extremes is not valid; the under-estimation of rainfall intensity values may lead to the failure of critical infrastructure. This paper is focused on identifying the extent of non-stationary behaviour at different locations in Kerala. The annual maxima rainfall data prepared from daily time series was idealized into non-stationary Generalized Extreme Value (GEV) distributions, with time-varying parameters after rainfall disaggregation operation. Non-stationary rainfall intensities were estimated using different non-stationary models, and the best model was identified using Akaike Information Criteria (AIC). From the analysis using station-wise data, it was found that districts including Palakkad, Malappuram, Idukki and Pathanamthitta were experiencing significant non-stationarity in extreme precipitation events. Non-stationary rainfall extremes were concentrated at Eastern regions of Kerala compared to coastal and midlands of Kerala.

Keywords: Rainfall, IDF curve, Non-stationarity, Return Period, GEV distribution, Design

1. Introduction

Human activities in the past century have caused an increase in global temperature. It is well proven that the rising temperature enhances the water holding capacity of the atmosphere by about 7% per 1⁰C, and higher atmospheric water vapour can lead to more extreme precipitation events. Consequentially, global warming increases the risk of climatic extremes, including floods and damage to infrastructures such as dams, roads and sewer, and stormwater drainage systems. Intensity-Duration-Frequency (IDF) curves are potential tools usually used for the design of such infrastructure. Traditionally, IDF curves are developed based on the assumption that return periods of precipitation



extremes will not change over time, but recent studies are showing that this assumption is not valid in a changing climate [1] and it may lead to underestimation of intensity in a non-stationary (NS) environment [2]. In the past decade, numerous researchers performed the studies to develop the NS IDF curves in different parts of the world [3-11]. These studies differ in the approaches followed and datasets in developing IDF curves in a non-stationary environment [12]. The simplest of the case is considering time-varying parameters of Generalized Extreme Value (GEV) distribution of annual maximum rainfall series of the past period. Many of the studies used the annual maxima rainfall series while few studies followed a partial duration series and peak over threshold approach for developing IDF curves [8, 13]. Mondal and Mujumdar [14] given the first comprehensive of Non-stationarity of IDF relationships in India, but the study was primarily based on the daily gridded data. Even though simplest approach for accounting the concept of changing return period is by considering time-varying distribution parameters, some researchers made in-depth studies on the use of appropriate covariates such as climatic oscillations for developing IDF curves [15, 16].

In view of the recent floods of 2018 and 2019 experienced in the coastal state of Kerala, it is important to identify the locations in the state which are susceptible to the non-stationary precipitation events. In some places, even though the effect of those changes is subtle now, it may become severe in the future. It may help for the regionalization of Kerala according to the susceptibility of different regions towards non-stationary rainfall intensities and eventually help in avoiding the risk of underestimation of precipitation extremes. In short, this study aims to get the spatial pattern on non-stationary intensity values to get more insights about the possible locations in Kerala which experience significant non-stationary climatic extremes. The specific objectives of this paper include (i) developing IDF curves for fourteen gauging stations over Kerala using the annual maximum daily data for the non-stationary and stationary cases (ii) identification of the critical locations/regions of significant changes in rainfall intensities. The following sections briefly outline the method used in the study, the data details used in the study, the results of developed IDF curves along with relevant discussion and finally the important conclusions drawn from the study.

2. Materials and methods

Rainfall IDF curve is a mathematical function that relates the rainfall intensity with its duration and frequency of occurrence. IDF curves are commonly used in hydrology for flood forecasting and civil engineering for urban drainage design. IDF curve graphically represents the probability of occurrence of particular rainfall intensity for a particular duration. The annual maxima rainfall approach is the most popular approach for developing IDF curves, and the annual maxima series for different durations are generally developed from the hourly rainfall information. The extreme value I (EVI) based frequency factor is the simplest approach for developing IDF curves; however, the use of three-parameter GEV distribution is more realistic and generalized one in developing IDF curves. Here the first step was to estimate the location (μ), scale (σ) and shape (γ) parameters using maximum likelihood method. After obtaining the parameters, design rainfall intensities are calculated using Eqn. (1)

$$x_T = \mu + \frac{\sigma}{\gamma} \left[-1 + \left\{ -\ln \left(1 - \frac{1}{T} \right) \right\}^{-\gamma} \right] \quad (1)$$

The above-given equation was derived from the cumulative distribution function (CDF) of GEV distribution in which X_T represents the rainfall intensity for a given return period and duration. These are based on the assumption of stationary that the parameters are static (time-invariant), and the return period is not changing. But in a changing climate scenario, this assumption becomes unrealistic, and we need to develop the non-stationary IDF curves by considering the distribution parameters are time-varying [17]. Here, location and scale

parameters are assumed to change with time while the shape parameter is kept constant. The Linear variation of location parameter and both linear, as well as the exponential variation of scale parameter, is considered for different non-stationary models. A combination of these variations is used to develop non-stationary IDF curves. The time-varying location and scale parameter can be expressed as,

- $\mu_t = \mu_0 + \mu_1 t$ (linear variation of location parameter)
- $\sigma_t = \sigma_0 + \sigma_1 t$ (linear variation of scale parameter)
- $\sigma_t = \exp(\sigma_0 + \sigma_1 t)$ (exponential variation of scale parameter)

Non-stationary rainfall intensities were estimated for all stations, corresponding to all durations by considering the following five models:

- i. Model 1: Location parameter is linearly varying
- ii. Model 2: Scale parameter is linearly varying
- iii. Model 3: Scale parameter is exponentially varying
- iv. Model 4: Location and scale parameters are linearly varying
- v. Model 5: Location parameter is linearly varying, and scale parameter is exponentially varying

Similar to the stationary methods, the first step was the estimation of parameters using the maximum likelihood method. Location parameter and scale parameter is fixed as 95th percentile of values obtained for μ_t and σ_t , respectively [1]. From the values of location, scale and shape parameters obtained, design rainfall intensity values were estimated similar to the stationary case. IDF curves were derived using the obtained values of design rainfall intensity. The daily rainfall data of 14 stations in Kerala for a period of 28 years (1991 to 2018) were collected from the India Meteorological Department (IMD) Trivandrum. The stations are considered in such a way that one representative station per district, which gives good spatial coverage of entire Kerala. The annual maximum daily rainfall data was extracted from this, which in turn was disaggregated to obtain 1hr, 3hr, 6hr, 12hr, 24 hr and 72hr for each station. Daily maximum rainfall data was analysed after it has been converted to hourly maximum rainfall data. The rainfall disaggregation was done using IMD formulae given in Equation (2)

$$P_t = P_{24} \left(\frac{t}{24} \right)^{1/3} \quad (2)$$

Where, P_t = Annual maximum precipitation for 't' hour duration

P_{24} = Annual maximum precipitation for the 24-hour duration

Using the data obtained after rainfall disaggregation of annual maximum hourly rainfall data, stationary and non-stationary rainfall intensities were estimated for the 14 stations. Non-stationary rainfall intensities were estimated for all stations, corresponding to all durations by considering all the five models. In this case more importance is given to the changes in stationary and non-stationary conditions more than the values.

The Akaike's Information Criteria (AIC) values of each of the five non-stationary models, for different combinations of durations (1, 3, 6, 12, 24 and 72hrs) and return periods (2, 5, 10, 25, 50, 100 years) were calculated using equation (3).

$$AICc = -2\log L(\beta/X) + \frac{2k(k+1)}{n-k-1} \quad (3)$$

Where, k = No. of parameters

n = Sample size

β = Parameters (shape, scale and location) with respect to X

The model having minimum AIC value was selected as the best model. The stationary intensities, non-stationary intensities and the percentage deviations were plotted on Kerala map with the selected best model. Validation was done with 2018 rainfall data which resulted in 2018 flood having ~100 year return period. The curve was developed with 2018 data and then compared it with stationary and nonstationary curve developed for 100 year return period. Flow chart of the methodology used in the study is shown in Figure 1.

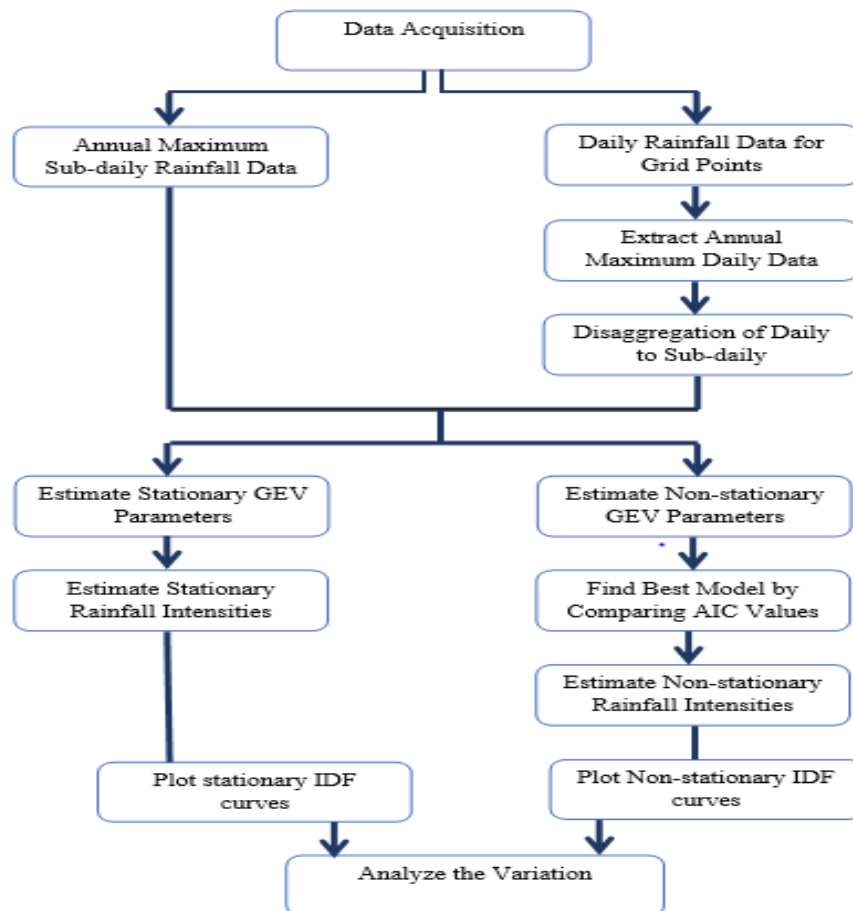


Figure 1 Flowchart showing methodology followed for developing IDF curves.

3. Results and discussion

Stationary and non-stationary rainfall intensities were estimated for all the 14 stations corresponding to different combinations of durations and return periods, and subsequently, the IDF curves were developed for these stations.

3.1 Stationary IDF curves

First, the stationary IDF curves for all the stations were developed using GEV distribution. Using the data obtained after rainfall disaggregation of annual maximum daily rainfall data, stationary rainfall intensities were estimated for all the stations, corresponding to different combinations of durations (1, 3, 6, 12, 18, 24, 36, 48, 60 and 72 hrs) and return periods (2, 5, 10, 25, 50, 100 years).

3.2 Non-stationary IDF curves

Stationary and NS- IDF curves were developed from annual maximum daily rainfall data and the percentage deviations of rainfall intensities in each case were calculated for all the stations. Different kinds of analysis were done by using the stationary as well as NS intensity values. The first analysis was done by comparing the stationary and nonstationary curves of each model (parameter combinations) for all the stations. The best non-stationary model was identified for each station after calculating AIC values. The model with minimum AIC value represents the best model. Table 1 represents the best fitted non-stationary model for the representative station of each district.

Table 1 Stations and their best fitted non-stationary models

Station/District	Best Model	AIC Value	Station/District	Best Model	AIC Value
Thiruvananthapuram	NS model1	-52.91	Thrissur	NS model1	-44.93
Kollam	NS model5	-73.03	Palakkad	NS model5	-55.16
Alappuzha	NS model4	-65.55	Malappuram	NS model4	-33.00
Pathanamthitta	NS model2	-47.44	Kozhikode	NS model4	-41.60
Kottayam	NS model4	-75.02	Wayanad	NS model2	-50.77
Idukki	NS model4	-47.099	Kannur	NS model4	-27.88
Ernakulam	NS model4	-62.99	Kasargod	NS model3	-56.48

From the results, it is clear that 50 % of the stations (7 stations) NS model 4 as the best model. i.e., linearly varying scale parameter constitutes the best non-stationary model. NS model 1, 2 and 5 are found to be the best for two stations each while for Kasargod station; NS model 3 is found to be the best.

For the better understanding, stationary and non-stationary rainfall intensities for Thiruvananthapuram station corresponding to different durations and return periods are given in Table 2. From Table 2 developed for Thiruvananthapuram district, it is clear that the non-stationary rainfall intensity estimates are significantly higher than the stationary rainfall intensity estimates, but each model behaved differently. In model 1, the variation between stationary and non-stationary values goes beyond 14%. It goes beyond 30%, 30%, 40%, and 40% in model 2, 3, 4 & 5 respectively. The major variation was observed in the case of the 100-year return period in all models under consideration.

3.3 Dependency of duration and return period on non-stationarity

The variation between stationary and non-stationary curves was also analyzed by plotting it separately corresponding to each return period. The most sensitive result was obtained for the station of Palakkad district. From the analysis, it was found that the major variations are observed in shorter durations as well as longer return periods. Different stations were showing

different behaviour in non-stationary rainfall estimates according to the variation of return periods.

From the graphical plot, it was found that generally non-stationary intensity values are inferred to be higher than stationary values. From the analysis, it can be generalized or summarized that as duration decreases the non-stationary effect on IDF increases. Also, as return period of the rainfall event increases non-stationarity become predominant. So the duration of rainfall event and non-stationarity effect of climate is inversely proportional and return period of the rainfall event, and non-stationarity in climate are directly proportional. Further, based on the best fit model stationary and non-stationary curves are plotted for each district, and percentage variation in each case was estimated and analysed, but the variation in intensity between NS and S case for each station is different. Palakkad, Idukki, Malappuram, Pathanamthitta, Kozhikode and Kannur show higher variation in IDF curve plotted in the two different approaches (stationary and non-stationary) (Fig 2).

Table 2 Stationary and Non- Stationary rainfall intensity estimates for Thiruvananthapuram station (in cm/hr)

Return Period (year)	Duration (hours)																			
	1	% Change	3	% Change	6	% Change	12	% Change	18	% Change	24	% Change	36	% Change	48	% Change	60	% Change	72	% Change
(a) Stationary Model																				
2	4.67		2.49		1.48		0.87		0.62		0.5		0.38		0.31		0.27		0.24	
5	6.06		3.3		1.97		1.17		0.83		0.67		0.51		0.42		0.36		0.33	
10	6.85		3.79		2.26		1.35		0.95		0.77		0.58		0.48		0.42		0.37	
25	7.73		4.35		2.59		1.56		1.09		0.88		0.66		0.55		0.47		0.42	
50	8.31		4.73		2.81		1.7		1.18		0.95		0.72		0.6		0.51		0.45	
100	8.82		5.09		3.01		1.82		1.27		1.02		0.77		0.64		0.54		0.47	
(b) NS Model 1																				
2	4.95	6.00	2.54	2.01	1.56	5.41	0.91	4.60	0.65	4.84	0.54	8	0.42	10.53	0.35	12.90	0.31	14.81	0.27	12.5
5	6.32	4.29	3.35	1.52	2.05	4.06	1.21	3.42	0.86	3.61	0.71	5.97	0.55	7.84	0.46	9.52	0.39	8.33	0.35	6.06
10	7.09	3.50	3.84	1.32	2.34	3.54	1.39	2.96	0.98	3.16	0.8	3.90	0.62	6.90	0.52	8.33	0.44	4.76	0.4	8.11
25	7.92	2.46	4.4	1.15	2.67	3.09	1.6	2.56	1.12	2.75	0.92	4.55	0.7	6.06	0.59	7.27	0.5	6.38	0.44	4.76
50	8.46	1.81	4.79	1.27	2.89	2.85	1.74	2.35	1.22	3.39	0.99	4.21	0.76	5.56	0.63	5.00	0.53	3.92	0.47	4.44
100	8.92	1.13	5.14	0.98	3.1	2.99	1.87	2.75	1.3	2.36	1.06	3.92	0.81	5.19	0.67	4.69	0.56	3.70	0.49	4.26
(c) NS Model 2																				
2	4.73	1.28	2.51	0.80	1.53	3.38	0.9	3.45	0.63	1.61	0.5	0	0.38	0	0.31	0	0.27	0	0.25	4.17
5	6.41	5.78	3.4	3.03	2.19	11.17	1.31	11.97	0.9	8.43	0.7	4.48	0.52	1.96	0.43	2.38	0.37	2.78	0.34	3.03
10	7.38	7.74	3.94	3.96	2.62	15.93	1.58	17.04	1.06	11.58	0.81	5.19	0.6	3.45	0.49	2.08	0.42	0.00	0.38	2.70
25	8.46	9.44	4.58	5.29	3.14	21.24	1.92	23.08	1.26	15.60	0.95	7.95	0.7	6.06	0.57	3.64	0.47	0.00	0.43	2.38
50	9.17	10.35	5.02	6.13	3.51	24.91	2.17	27.65	1.4	18.64	1.04	9.47	0.76	5.56	0.61	1.67	0.51	0.00	0.46	2.22
100	9.81	11.22	5.43	6.68	3.87	28.57	2.41	32.42	1.53	20.47	1.12	9.80	0.82	6.49	0.66	3.13	0.54	0.00	0.49	4.26

(d) NS Model 3																				
2	4.75	1.71	2.51	0.80	1.55	4.73	0.9	3.45	0.63	1.61	0.5	0	0.38	0	0.31	0	0.27	0	0.25	4.17
5	6.5	7.26	3.42	3.64	2.25	14.21	1.3	11.11	0.89	7.23	0.7	4.48	0.52	1.96	0.43	2.38	0.37	2.78	0.34	3.03
10	7.51	9.64	3.97	4.75	2.7	19.47	1.57	16.30	1.05	10.53	0.81	5.19	0.6	3.45	0.49	2.08	0.42	0	0.38	2.70
25	8.64	11.77	4.62	6.21	3.25	25.48	1.89	21.15	1.25	14.68	0.94	6.82	0.69	4.55	0.56	1.82	0.47	0	0.43	2.38
50	9.39	13.00	5.07	7.19	3.65	29.89	2.12	24.71	1.38	16.95	1.03	8.42	0.76	5.56	0.61	1.67	0.51	0	0.46	2.22
100	10.1	13.95	5.49	7.86	4.03	33.89	2.34	28.57	1.5	18.11	1.11	8.82	0.81	5.19	0.65	1.56	0.54	0	0.49	4.26
(e) NS Model 4																				
2	4.94	5.78	2.56	2.81	1.6	8.11	0.93	6.90	0.66	6.45	0.54	8	0.42	10.53	0.36	16.13	0.31	14.81	0.28	16.67
5	6.88	13.53	3.52	6.67	2.26	14.72	1.35	15.38	0.94	13.25	0.75	11.94	0.58	13.73	0.49	16.67	0.42	16.67	0.38	15.15
10	8.18	19.42	4.16	9.76	2.7	19.47	1.63	20.74	1.13	18.95	0.89	15.58	0.69	18.97	0.57	18.75	0.49	16.67	0.44	18.92
25	9.85	27.43	4.97	14.25	3.26	25.87	1.98	26.92	1.37	25.69	1.07	21.59	0.82	24.24	0.68	23.64	0.58	23.40	0.53	26.19
50	11.1	33.57	5.57	17.76	3.68	30.96	2.25	32.35	1.54	30.51	1.2	26.32	0.92	27.78	0.76	26.67	0.65	27.45	0.59	31.11
100	12.4	40.02	6.17	21.22	4.1	36.21	2.51	37.91	1.72	35.43	1.33	30.39	1.02	32.47	0.84	31.25	0.71	31.48	0.66	40.43
(f) NS Model 5																				
2	4.95	6.00	2.56	2.81	1.61	8.78	0.94	8.05	0.66	6.45	0.54	8	0.42	10.53	0.36	16.13	0.31	14.81	0.28	16.67
5	6.97	15.02	3.54	7.27	2.31	17.26	1.37	17.09	0.95	14.46	0.76	13.43	0.58	13.73	0.49	16.67	0.42	16.67	0.38	15.15
10	8.31	21.31	4.19	10.55	2.78	23.01	1.65	22.22	1.14	20.00	0.9	16.88	0.69	18.97	0.57	18.75	0.49	16.67	0.44	18.92
25	10	29.75	5.01	15.17	3.39	30.89	2.02	29.49	1.38	26.61	1.07	21.59	0.82	24.24	0.68	23.64	0.58	23.40	0.53	26.19
50	11.3	36.22	5.62	18.82	3.84	36.65	2.29	34.71	1.56	32.20	1.21	27.37	0.93	29.17	0.76	26.67	0.65	27.45	0.59	31.11
100	12.6	43.08	6.23	22.40	4.3	42.86	2.57	41.21	1.74	37.01	1.34	31.37	1.03	33.77	0.84	31.25	0.71	31.48	0.65	38.30

3.4 Model Validation

For the validation of the best-fitted model (parameter combination), annual maximum daily rainfall data of for selected districts in the year 2018 from IMD was used. The observed 2018 daily data was disaggregated to hourly for the different durations (1, 3, 6, 12, 18, 24, 36, 48, 60 & 72 hrs). Validation was done on Palakkad, Malappuram, Pathanamthitta and Idukki. Because the variation observed were more in these districts. As per the 2018 flood report by central water commission also these are the two most flood affected districts in Kerala. The validation results are as shown in Fig. 3.

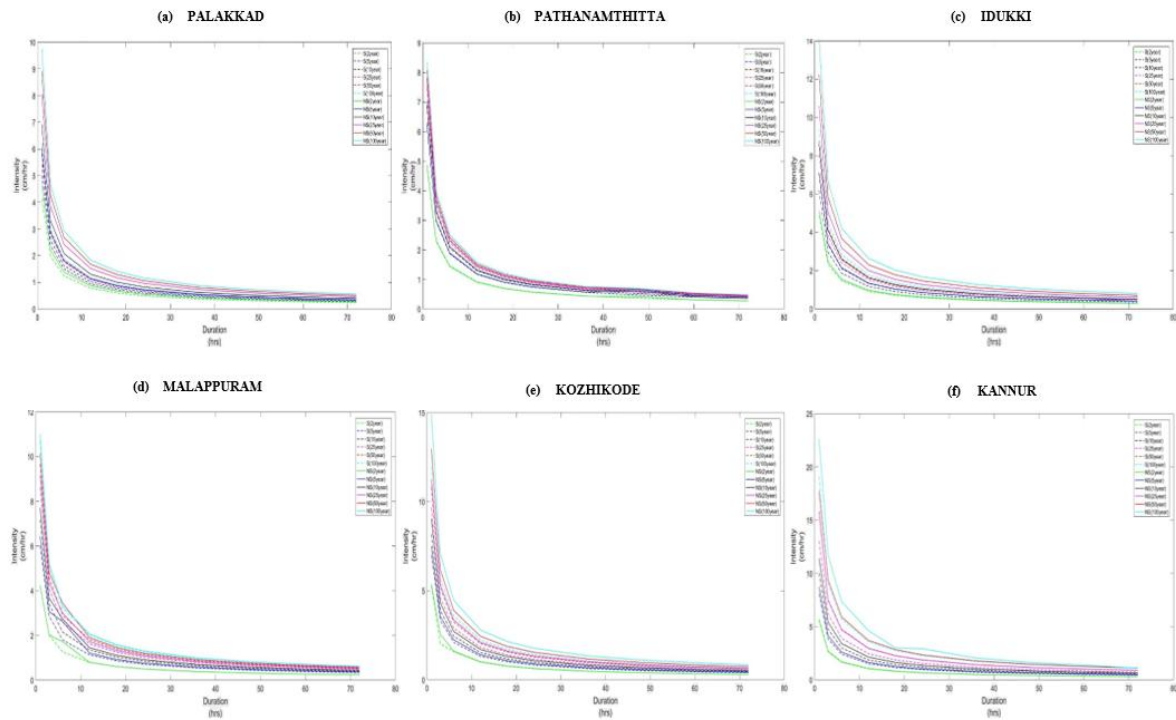


Figure 2 Stationary and non-stationary IDF curves for (a) Palakkad (b) Pathanamthitta (c) Idukki (d) Malappuram (e) Kozhikode (f) Kannur

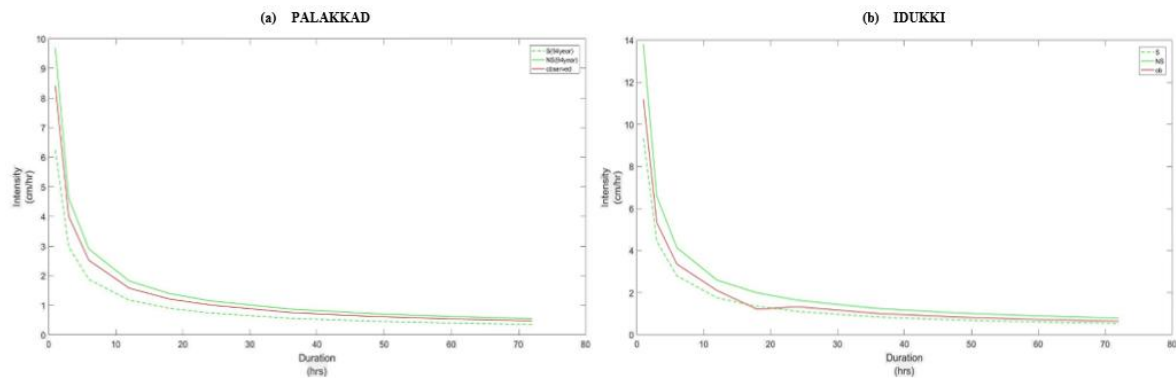


Figure 3 Stationary, non-stationary IDF curves and observed value curve for the year 2018 for (100yr return period) (a) Palakkad (b) Idukki

3.5 Spatial variability of IDF characteristics

After all these simulations, tabulations and calculations, spatial variability of non-stationary IDF curves for different stations along Kerala profile were studied and represented it over the plot of Kerala for better understanding. From the plot, we can easily identify the districts where non-stationarity causes a major impact on the design of infrastructures related to water. The plots were developed for the selected durations 3, 6, 12 and 24 hr. The plots obtained for 3 hour and 24 hour are shown in Fig. 4 and Fig. 5. From the distribution, the districts like Malappuram, Pathanamthitta, Palakkad and Idukki are showing higher variations in NS rainfall intensity estimates for larger return periods. Also, it is noticed that north-eastern parts of Kerala are showing higher levels of non-stationary behaviour compared to the western

parts of Kerala. Geographically, the former locations belong to the high land, while the latter belongs to the coastal regions of Kerala.

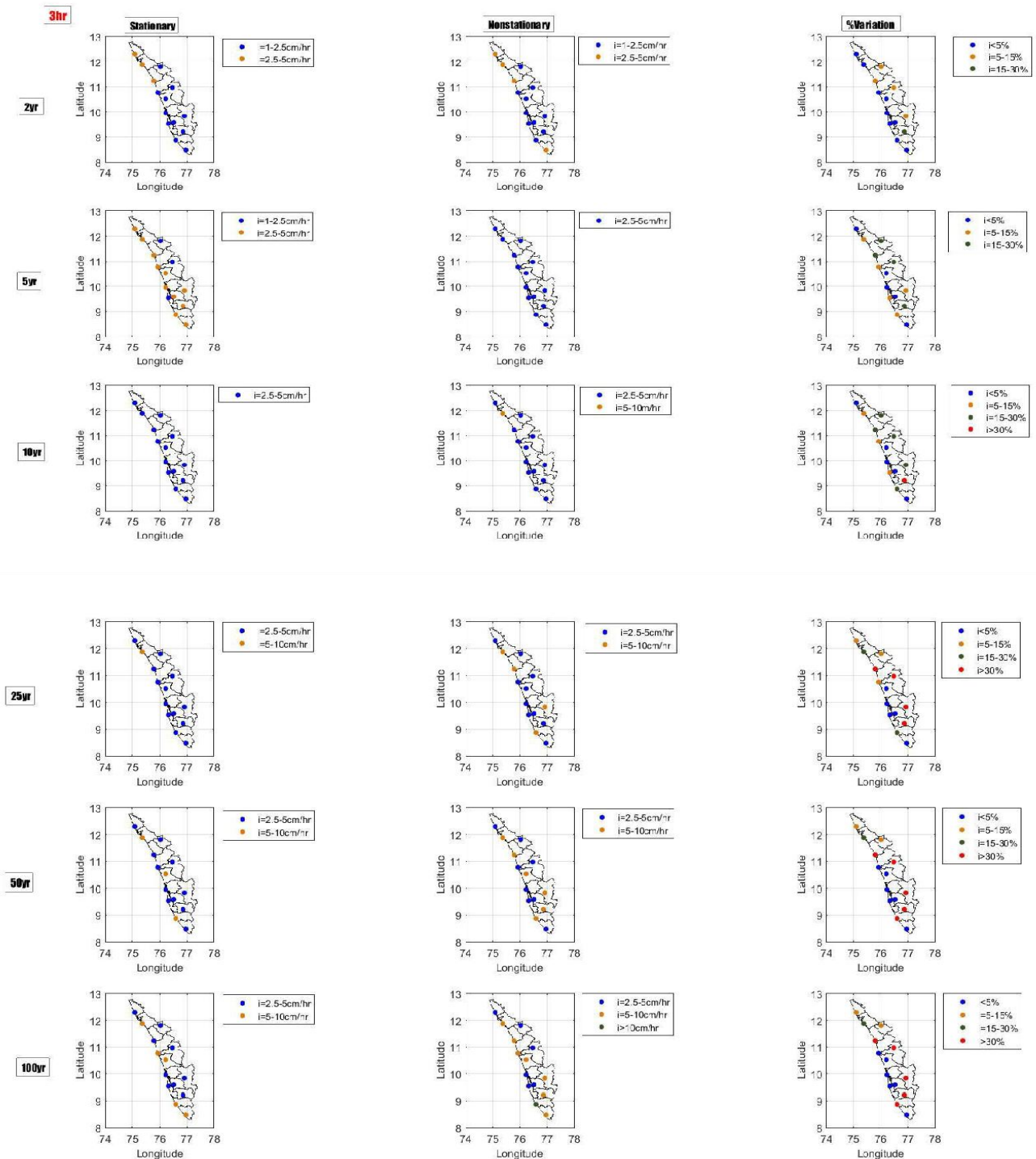


Figure 4 Stationary & non-stationary intensities and percentage variation for 3 hr duration

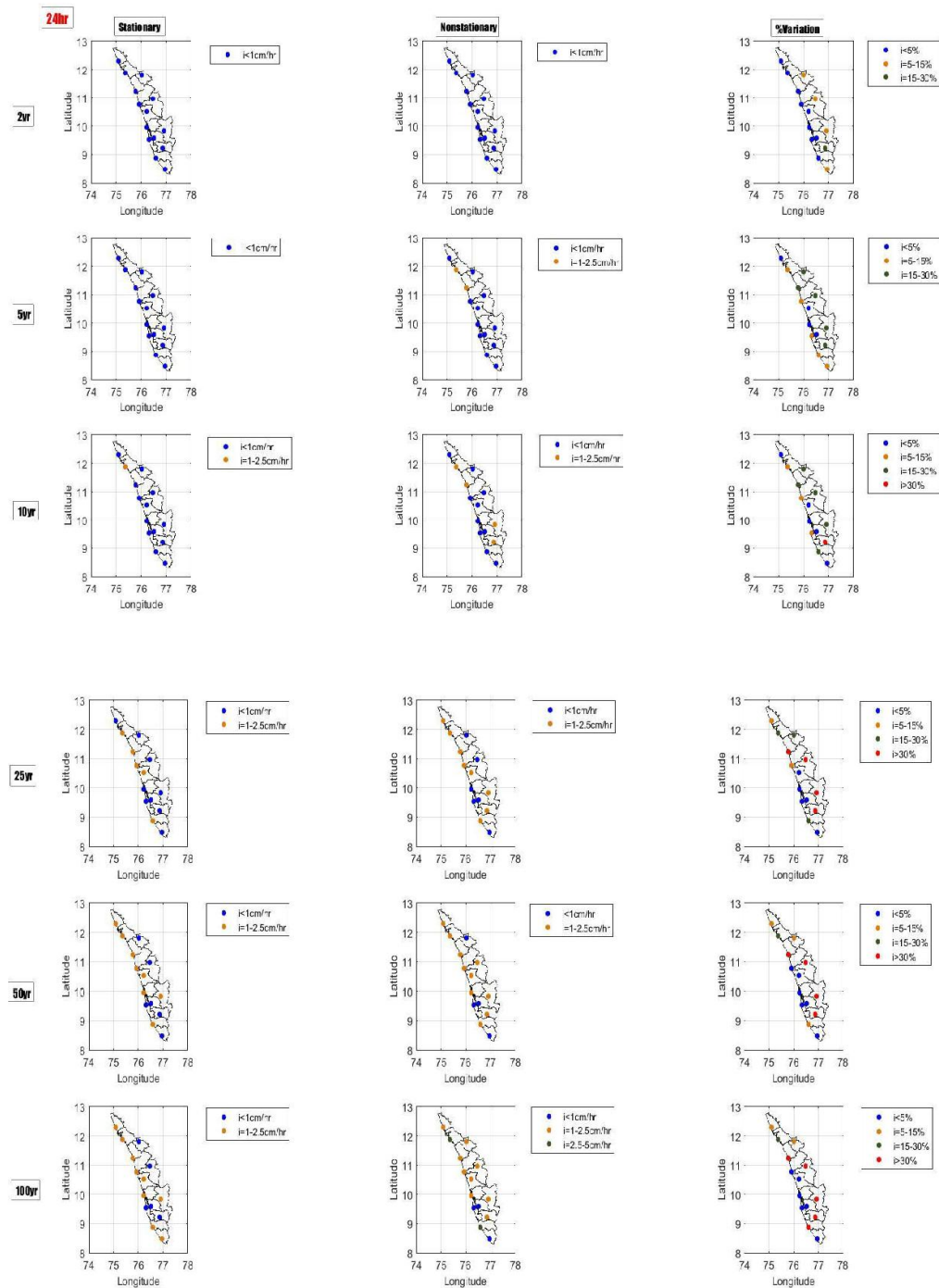


Figure 5 Stationary & non-stationary intensities and percentage variation for 24 hr duration

4. Conclusion

From the obtained results and their interpretations, it was identified that there exists significant non-stationary behaviour at different locations across the state. In the case of Thiruvananthapuram and Kozhikode districts, daily as well as hourly data were directly

available. Curve was developed in both already available hourly data and the disaggregated daily data. The obtained results were compared in order to find out whether the disaggregation influences the result or not. The finding was, the curve developed with hourly data shows more percentage variation between stationary and non-stationary intensities than disaggregated one. But the change obtained in both cases was not much. This finding indicates that the results obtained from disaggregated data are safe to develop stationary as well as non-stationary IDF curves. By conducting such an analysis, the following conclusions were obtained:

- Short duration and longer return periods show a high level of nonstationary behaviour than long-duration short return periods
- Across the whole Kerala, districts like Kozhikode, Malappuram, Palakkad, Idukki, Pathanamthitta and Kollam are experiencing very high levels of non-stationary behaviour (greater than 30% underestimation, in average for different combinations of durations and return periods, in stationary rainfall intensities) in rainfall extremes.
- Palakkad and Pathanamthitta were showing a non-stationarity with even greater than 50% variation for some combination of durations and return periods.
- North-Eastern parts of Kerala are showing higher levels of non-stationary behaviour compared to the western parts of Kerala.

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