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Coastal Flood Disaster in Sri Lanka-May 2017: Exploring Distributional Changes in Rainfall and Their Impacts on Flood Risk

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ABSTRACT

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Coastal communities, their livelihoods, and the coastal ecosystems of Sri Lanka are vulnerable to extreme rainfall events. In May 2017, the southern and southwestern coastal regions of Sri Lanka experienced devastating floods, which caused nearly 122 deaths. In light of this, exploring distributional changes in extreme rainfall series recorded across Sri Lanka are crucial to understand flood risk in the context of climate variability and change. This study was focused on investigating possible distributional changes in annual maximum daily rainfall (ADMR) over time for the affected coastal regions in Sri Lanka using a quantile regression approach in a Bayesian framework. A simplified nine–category distributional change scheme based on the empirical probability density functions of two years (*i.e.,* the first year and the last year) was used to determine the distributional changes in ADMR. This study examined the trends of ADMRs for seven stations in coastal regions of Sri Lanka for the period of 1960 – 2015. Three categories in terms of distributional change in ADMR were identified for these regions. One station showed an upward trend in distributional change in ADMR, which could indicate high probability of extreme rainfall. The rest of the stations showed a downward trend in the quantiles, which could indicate low probability of extreme rainfall. Further discussion of the possible reasons for the occurrence of the coastal flood disaster in May 2017 in Sri Lanka is provided below.

ADDITIONAL INDEX WORDS: *Coastal flood, Sri Lanka, quantile regression.*

INTRODUCTION

The southwest monsoon season in Sri Lanka typically peaks during late May to the beginning of June, with prevailing winds from the south and southwest moving toward the Bay of Bengal (Wickramagamage 2016; Wikipedia, 2017). Many people have claimed that monsoon rains are the most likely cause of natural disasters in Sri Lanka (Disaster Management Center, 2012), and the onset of the southwestern monsoon season (i.e., May-June) is involved in the periodic annual floods and landslide disasters (United Nations Office for the Coordination of Humanitarian Affairs, 2016; Ratnayake and Herath, 2005; Zubair, 2014). Furthermore, the western slopes of Sri Lanka receive the highest rainfall on the island from May to September. In this context, the western slopes of Sri Lanka are highly prone to disasters due to the high population density (i.e., Colombo district – 3,438/km^2; Gampaha district – 1,719/km^2; Galle district – 658/km^2) (Department of Census and Statistics, 2017; Zubair, 2004).

However, on May 18 –30, 2017, continuous heavy rainfall brought by the southwest monsoon (or summer monsoon) season triggered flooding in most of the regions (i.e., 15 out of 25 administrative districts) including the south, southwestern, and northeastern coastal regions of Sri Lanka. Flooding was worsened by the arrival of the precursor system to Cyclone Mora with the depression at the Bay of Bengal. Floods and landslides claimed nearly 212 lives and left 79 people missing (International Organization for Migration, Sri Lanka, 2017b; Wikipedia, 2017). According to the data sources by the Disaster Management Center, Government of Sri Lanka, approximately 0.58 million people were affected, and 30,000 houses were destroyed (International Organization for Migration, Sri Lanka, 2017a). Furthermore, the disaster was exacerbated due to the Dengue outbreak in the flooded areas.

Background and Goal

Sri Lanka is highly affected by weather-related hazards due to its location as a small island in the Indian Ocean, between two monsoon paths (Disaster Management Center, 2012). Therefore, coastal communities, their livelihoods, and coastal ecosystems of Sri Lanka are highly vulnerable to many natural hazards. Tsunamis, flooding due to storm surge, coastal erosion, sea level rise, sea water intrusion, and vector borne diseases are a few of the types of coastal hazards observed in Sri Lanka. In 2004, the worst natural disaster in Sri Lanka, a tsunami, devastated the country and caused 35,000 deaths (Hays, 2013). Furthermore, Sri

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Lanka is vulnerable to cyclones generated mostly in the southern part of the Bay of Bengal (Wijetunge and Marasinghe, 2015). Gonnert *et al*. (2001) noted three tropical cyclones in 1964, 1978, and 1992 that caused extensive damage due to rain and storm surges.

Most of the natural hazards that affect Sri Lanka have a hydro-meteorological background. Many meteorologists and climatologists have described the meteorology behind the past disasters, such as cyclones and floods (Bamford, 1926; Ekanayake, 1968; Jameson, 1922, 1927, 1937; Jayatillake Banda, 1992; Suppiah, 1982; Thambyapillay, 1959). Although Sri Lanka is experiencing consecutive natural hazards, there has been little application of hydro-meteorological knowledge to hazard analysis and preparedness. To contribute to mitigating this lapse, a meteorological analysis of the recent coastal flood disaster in May 2017 was presented as part of a sustained effort to undertake meteorological application for hazard warnings in Sri Lanka.

METHODS

Seven coastal stations were selected in May 2017 based on severity of flooding. The original data contained daily rainfall records for the period between 1960 and 2015. The quality of data was assessed based on the record length and the proportion of the missing values (*i.e.,* less than 10% missing values). Furthermore, the monthly total rainfall data for each station were compared with CRU 3.4 (Climate Research Unit 3.4) rainfall data in order to produce more robust results. The CRU data are available for review at https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_3.22/.

Bayesian Quantile Regression (BQR)

Annual daily maximum rainfall (ADMR) was used as the index to identify rainfall trends for these stations. For the analysis of distributional changes in ADMRs, a quantile regression model (Equation 1) was developed in which all of the quantile functions are simultaneously estimated within a fully Bayesian framework as follows:

$$y_{i,q} = \eta_{i,q} + \epsilon_{i,q} = x_i'\alpha_q + \epsilon_{i,q} \tag{1}$$

where x_i' is a vector of regressors, α_q is a vector of regression coefficients for the qth conditional quantile, $\epsilon_{i,q}$ is an unspecified quantile-specific error term, for which no distribution is specified other than the constraint $Q_{\epsilon_{i,q}}(q) = 0$ and is estimated by minimizing the asymmetrically weighted absolute deviations through linear programming.

Posterior estimates can be subsequently obtained using Bayesian updates conditioned on the exponential random variable U. Using the above stochastic representation, the proposed quantile regression model can be rewritten as follows (Equation 2):

$$y_{i,q} = \eta_{i.q} + \frac{1-2q}{q(1-q)}U_{i,q} + \sqrt{\frac{2U_{i,q}}{\delta^2 q(1-q)}}z_i, \tag{2}$$

where $U_{i,q}$ and $Z_{i,p}$ are subject-specific values of U and Z, respectively, and $\eta_{i,p}$ is the estimation by least square for the ith year and qth quantile.

Bayesian Inference for Parameter Estimation

The Bayesian inference framework was adopted to enable the inclusion and improved consideration of the uncertainties in the proposed quantile regression model parameters. For the parameters of the proposed model, the regression parameters can be any real number, and the asymmetrical Laplace distribution (ALD) precision parameter $\delta^2{}_q$ should be greater than zero. Hence, assumptions were made as a conjugate normal prior to regression coefficient θ_q and a gamma prior to the ALD precision parameter $\delta^2{}_q$.

Later, the Markov Chain Monte Carlo (MCMC) method was adopted to sample from the posterior distribution. After setting initial values of the model parameters, the algorithm iterates the following steps. (1) Sample θ_q from its full conditional normal distribution. (2) Sample $\delta^2{}_q$ from its full conditional gamma distribution. (3) For all i, update the inverse latent weights U_i^{-1} for its exponential distribution using previously sampled $\delta^2{}_q$. (4) Steps 1 to 3 are repeated until a sufficient number of samples for the proposed model in year i are obtained. In this study, 50,000 simulations were performed with 30,000 burnouts for three chains. The convergence of the parameter was evaluated using the Gelman–Rubin (GR) statistic (Gelman *et al.*, 2014) with all values less than 1.1, suggesting convergence after 50,000 iterations with a 1,000 cycle burn-in.

Categorical Distributional Change Detection Approach Using Bayesian Quantile Regression

The non-parametric Mann-Kendall (MK) test was used to determine the linear trends in rainfall extremes (Gilbert, 1987; Kendall, 1975; Mann, 1945). The Kwiatkowski–Phillips–Schmidt–Shin (KPSS) test (Kwiatkowski *et al*., 1992) and Augmented Dickey-Fuller (ADF) test (Dickey and Fuller, 1981) were used to determine stationarity in the rainfall extremes. Based on the results of a previous study (Shiau and Huang, 2015), a Bayesian quantile regression-based distributional change detection approach was proposed. Shiau and Huang (2015) identified nine possible categories in terms of distributional changes depending on both changes of scale and location of probability density functions (PDF). The Bayesian Quantile Regression (BQR) was implemented over a wide range of quantiles in order to drive the empirical PDFs. In this study, nine quantiles were selected (*i.e*., from 0.05 to 0.95 with an increment of 0.1).

RESULTS

All of the selected stations were qualified from the quality assessment procedure and had high correlations with the CRU 3.4 data. Therefore, these data could be used for further analysis. The selected stations are as shown in Table 1.

Table 1. *Stations and their severity of impact by the flooding of May 2017.*

Station Name	District	Severity of impact*
Colombo	Colombo	High
Ratmalana	Colombo	High
Galle	Galle	High
Hambanthota	Hambanthota	Medium
Katunayake	Gampaha	Medium
Batticaloa	Batticaloa	Low
Trincomalee	Trincomalee	Low

* Severity of impact is grouped according to number of people affected (*i.e.,* High – more than 10,000, Medium – 1000–9999, and Low – less than 999).
Source: United Nations-Sri Lanka, 2017

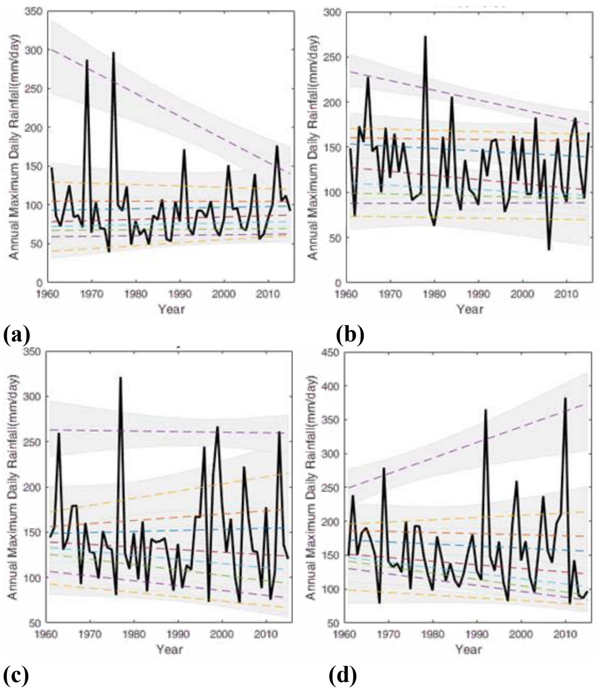
Rainfall Trends

Based on the MK test, there was no significant trend for any of the stations, with a 95% confidence interval. All of the stations showed statistically significant stationarity at a 5% significance level based on the KPSS test. On the other hand, the Trincomalee and Galle stations showed statistically significant stationarity at a 5% significance level based on the ADF test.

Three distributional categories based on the changes of quantile regression lines for the ADMRs were identified over the selected stations: a) Category I – Upward convergent lines, b) Category VII - Downward convergent lines, and c) Category IX – Downward divergent lines.

Table 2. *Distributional change categories for the stations.*

Category	Stations
Category I	Hambanthota
Category VII	Trincomalee
Category IX	Katunayake, Ratmalana, Galle, Colombo, Batticaloa



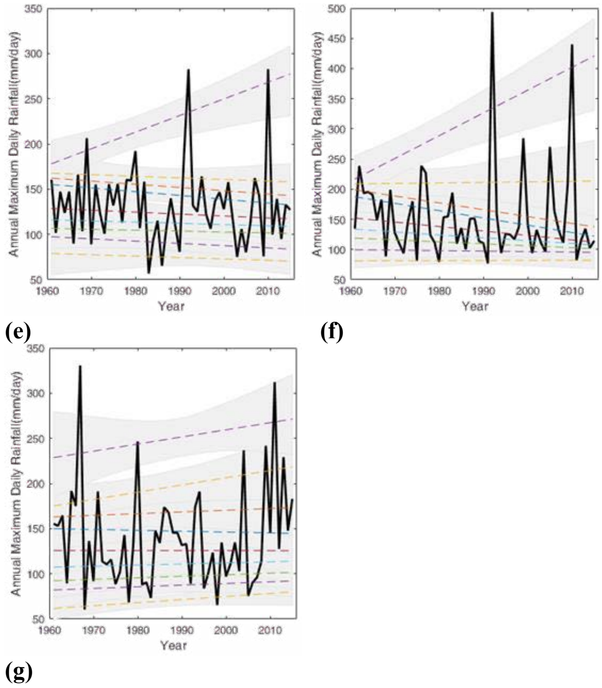


Figure 1. Distributional changes of ADMR at the stations: (a) Hambanthota, (b) Trincomalee, (c) Katunayake, (d) Ratmalana, (e) Galle, (f) Colombo and (g) Batticaloa

DISCUSSION

Based on severity, the southwestern coastal regions were greatly impacted by the flood in May 2017. The smallest impact was observed in the northeastern coastal regions of Sri Lanka.

Distributional Changes in the Rainfall of the Station Most Impacted by Flood

As seen in Table 1, the Colombo and Galle districts were highly impacted by the flood in May 2017. The results showed Colombo, Galle, and Ratmalana stations had a decreasing trend in ADMR (Table 2). Furthermore, the mentioned stations displayed an increasing trend in the upper most quantile, which could indicate a high probability of extreme high rainfall events (Figure 1 (f), (e) and (d), respectively). Therefore, high intensity, short duration rainfall could make a high flood impact for these districts. Wickramagamage (2016) identified mean annual and mean seasonal rainfall of Colombo, Galle and Ratmalana station had an increasing trend during recent decades. For Galle station, seasonal monsoon rainfall increased between May and September during 1966-2015 (Karunathilaka, *et al*., 2017). Therefore, Colombo and Galle districts are highly prone to flooding due to distributional changes of daily, seasonal and annual rainfall.

Distributional Changes in the Rainfall of the Station Moderately Impacted by Flood

The Gampaha district had medium impact from the flood in May 2017 (Table 1). The Katunayake station, which represents the Gampaha district, showed a decreasing trend in rainfall for

ADMR from 1960 – 2015 (Table 2). However, as seen in Figure 1 (c) the upper most quantile showed a more or less constant trend, and the rest of the upper quantiles (*i.e.,* 6th, 7th, and 8th quantiles) showed an increasing trend of ADMR. Therefore, an increasing trend in ADMR indicated high probability of extreme rainfall events that could cause flooding. Further, Wickramagamage (2016) revealed mean annual and mean seasonal rainfall of the Gampaha district showed increasing trend during past decades.

The Hambanthota station was in the category that showed an increasing trend in the distribution of ADMR (Table 2). Wickramagamage (2016) also mentioned that the Hambanthota station had an increasing mean annual rainfall trend. Furthermore, the lower quantiles showed an increasing trend in ADMR (Figure 1 (a)), which also highlighting that the presence of low annual maximum daily rainfall could lead to flooding in Hambanthota district. . However, the uppermost quantile showed a decreasing trend for ADMR. Further, seasonal monsoon rainfall during May to September also showed decreasing trend (Karunathilaka, et al., 2017) and could lead to less flood impact in Hambanthota district.

Distributional Changes in the Rainfall of the Station Least Impacted by Flood

As shown in Figure 1 (b), the uppermost quantile showed a decreasing trend in ADMR for the Trincomalee station. This result implied that there was a low possibility of observing extreme flood situations with the presence of high ADMRs for the Trincomalee district.

However, a few of the intermittent quantiles of the Trincomalee station showed an increasing trend. But the impact from distributional changes of intermittent quantiles for flooding are not considerable.

Distributional changes in ADMR of the Batticaloa station showed a decreasing trend (Table 2). The lower and middle quantiles showed a decreasing trend, but it was inconsequential. Furthermore the seasonal monsoon rainfall between May to September for the Batticaloa district had decreasing trend during past decades (Karunathilaka, *et al*., 2017). Therefore, Batticaloa district may not observe the frequent flood impact as compared to other districts. However, the uppermost and lowest quantiles showed an increasing trend, indicating that there is a high probability of a flood event with high intensity rainfall (Figure 1 (g)).

Furthermore, Wickramagamage (2016) stated that both the Trincomalee and Batticaloa stations had increasing trends in mean annual and mean seasonal pentads based on ordinary linear regression curves.

Other Hydro-Geological and Social Influences on the Flood of May 2017

In addition, the southern and southwestern coastal regions (*i.e.,* Colombo, Ratmalana, and Galle stations), which were highly impacted by the flood of May 2017, were located on the windward side of the southwestern monsoon, while the northeastern and eastern coastal regions (*i.e*., Batticaloa and Trincomalee stations) were on the leeward side of the southwestern monsoon. In addition, tropical cyclones that formed in the Bay of Bengal could have aggravated the disaster impact due to monsoon rainfall (Disaster Management Center, 2012). In 2017, Cyclone Mora was developed in the Bay of Bengal during the month of May and aggravated the impact of monsoon rainfall during May to September in Sri Lanka.

Sri Lanka is a country renowned for its abundant water resources, which include 103 rivers, exceptionally designed minor and major irrigation systems, and significant groundwater resources (Ministry of Environment and Natural Resources, 2008). Southwestern coastal regions (*i.e.,* Gampaha, Colombo, and Galle districts) contain shallow coastal sand aquifers, shallow alluvial aquifers, and southwestern lateritic (Cabook) aquifers. The Hambanthota districts house a shallow regolith aquifer. On the other hand, northeastern coastal regions (*i.e*., Trincomalee and Batticaloa districts) contain shallow aquifers on raised beaches (Panabokke and Perera, 2005). These aquifers are shallow and quickly refill with high intensity short duration rainfall, which can cause flooding in the aforementioned coastal regions.

Northeastern and eastern coastal regions of Sri Lanka have reddish brown earth (RBE) soils that can become waterlogged due to the perched water table occurring directly above the subsoil during wet periods (Punyawardene, 2008; NSW Government-Department of Primary Industries, 2017). Therefore, the Trincomalee and Batticaloa districts are prone to mild flooding with heavy rainfall due to the low drainage capacity of the soil.

However, sea level rise is prominent in western coastal regions of Sri Lanka. Out of the six study districts, Hambanthota, Galle, and Gampaha are more prone to sea level rise in the next 25 years (Disaster Management Center, 2012). Therefore, tidal impact during extreme rainfall events can cause flooding in the mentioned districts.

As discussed earlier, most of the western coastal regions are densely populated. Therefore, a greater number of people are affected in a natural disaster. Furthermore, urban planning is not well-suited to mitigate flood hazards. Land use changes including deterioration of natural wetlands located in the southwestern coastal region by anthropogenic action could retard the natural drainage of flood waters. Therefore, these regions are prone to flooding in both low intensity, high rainfall and high intensity, low rainfall conditions.

CONCLUSIONS

Investigating the Bayesian quantile regression of ADMR over coastal stations provided comprehensive knowledge on distributional changes in quantiles, which indicated high possibility of flooding. Furthermore, the distributional changes were categorized by non-stationarity, which was largely defined by changes in location and scale parameters of the probability distribution.

The direction of the monsoon and typhoon pathways, soil type, type of underlying aquifer, land use changes, and social and anthropogenic activities could lead to increased flood impacts in the coastal regions of Sri Lanka.

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