

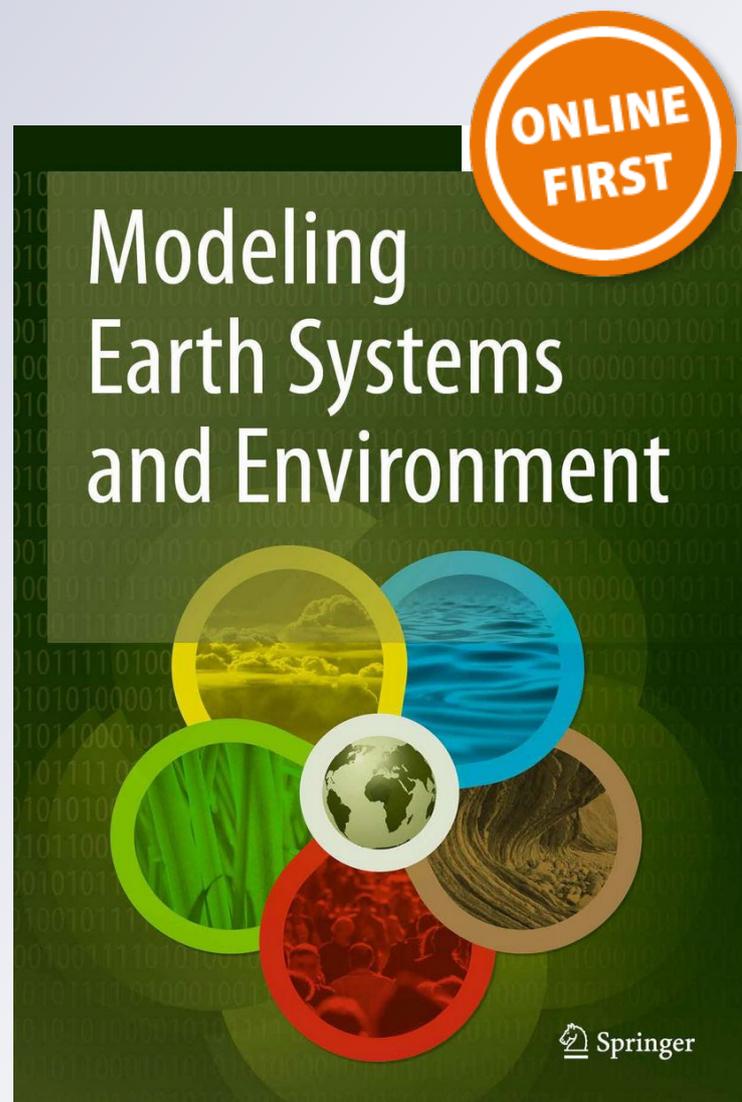
Modeling the concurrent impact of extreme rainfall and reservoir storage on Kerala floods 2018: a Copula approach

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Modeling the concurrent impact of extreme rainfall and reservoir storage on Kerala floods 2018: a Copula approach

A. Anandalekshmi¹ · Seenu T. Panicker¹ · S. Adarsh¹ · A. Muhammed Siddik¹ · Sajna Aloysius¹ · M. Mehjabin¹

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Abstract

This study investigates the concurrent impact of reservoir storage and extreme rainfall on the devastating Kerala floods 2018 using Copulas. First, the effect of storage of four major reservoirs Idukki, Idamalayar, Kakki and Kallada is investigated by developing storage curves. It is noticed that in the four reservoirs, the storage level was above the decadal mean storage in most of the days of July–August period of 2018. An analysis on the storage levels of the four reservoirs showed that the water level crossed the spillway crest level of the respective reservoirs by July 26, 2018 and the controlled release might have helped in alleviating the flood disasters. In the Copula-based modeling, first, the marginal distribution of monthly storage and rainfall of the four reservoirs are developed and it was found that the generalized Pareto (GP) distribution was fitting best for all the storage data. The exponential fit was found to be the best for rainfall of all reservoirs except that of Kakki. Subsequently, the joint probability of reservoir storage and rainfall is investigated using three popular Copulas of Archimedean family namely Gumbel–Hougaard (GH), Clayton and Frank and the best Copula is identified for each case. The return period curves are developed for both joint and conditional cases using the best fitted Copula. The sensitivity analysis of joint return period showed that the rainfall of Kakki and Idukki at 2018 was extreme and the effect of rainfall is dominant in these reservoirs.

Keywords Copulas · Flood · Rainfall · Return period · Storage

Introduction

Flood is one of the most debated natural disasters, which is a period of abnormal rainfall in a region and leads to natural calamities of different forms. Therefore, monitoring, prediction and analysis of flood are important. Kerala, the state located at the south west coast of India, popularly known as the ‘Gateway of Indian Monsoon’, has an average annual rainfall of 3000 mm, which receives about 70% of the rain during the south west monsoon period (June–September). The high intensity storms prevailing during the monsoon period results in heavy discharges in all the rivers and the steep and undulating terrain of Kerala results in faster runoff processes through the streams.

Kerala experienced an abnormally high rainfall from 1 June 2018 to 19 August 2018. As per India Meteorological Department (IMD) data, Kerala received 2346.6 mm of

rainfall from 1 June 2018 to 19 August 2018 in contrast to an expected 1649.5 mm of rainfall (about 42% above the normal). The abnormal rainfall in 2018 resulted in an unprecedented and severe flooding in 13 out of 14 districts in the State in the year 2018. The flood was a near-century return period flood, and such a disaster was experienced by the State in the past in 1924. The flood resulted in the loss of life of more than 400 people and huge property loss. Subsequently, lot of debates started among researchers on the relative role of different causative factors on the damages resulted from the Kerala flood 2018. Mishra et al. (2018) performed a study on the impact of extreme rainfall and storage reservoirs considering seven major reservoirs, by developing the storage curves and depth–duration–frequency curves of rainfall. But it was reported that the study considered the daily gridded rainfall for the analysis and the use of station wise rainfall data and reservoir releases could have given a better picture of the scenario. Using the observations and simulations from the Variable Infiltration Capacity (VIC) model, Mishra and Shah (2018) showed that mean monsoon precipitation has significantly declined, while air temperature has significantly increased during 1951–2017

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period in Kerala. It was reported that the drying and warming trends during the monsoon season resulted in a declination in total and extreme runoff, while 1- and 2-day extreme precipitation and extreme runoff conditions in August 2018 exceeded substantially from the long-term 95th percentiles recorded during 1951–2017 period. They concluded that August 2018 flood was unprecedented and driven by anomalous atmospheric conditions due to climate variability rather anthropogenic climate warming. The severity of the Kerala flood of 2018 and the damage caused might have affected by several factors including land use/land cover change, antecedent hydrologic conditions, reservoir storage and operations, encroachment of flood plains and other natural factors (Mishra and Shah 2018). Sudheer et al. (2019) performed a detailed analysis on the hydrology of Periyar basin located in the central Kerala. The study reported the results and analysis of a modeling exercise using Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) to simulate and analyze the role of dams, as well as reservoir operations on the flood of August 2018. Based on the results, they explicitly stated that the operation of dams has no major role in damages experienced after the 2018 floods. Dixit et al. (2019) investigated the role of changing Land Use Land Cover (LULC) during 1985–2018 on the Kerala flood 2018. They done the coupling of the Weather Research and Forecasting (WRF) model with WRF-Hydro and investigated the impact of LULC changes on the flooding event. The calibrated version of WRF-Hydro was then forced with meteorological inputs from WRF and rainfall from TRMM satellite (for August 2018) to investigate the LULC sensitivity. Using various statistical measures, they found that the WRF–WRF-Hydro coupled model was able to simulate the discharge reasonably well. For the given meteorological forcing, different LULC conditions (1985, 1995, 2005 and 2018) showed varying degree of changes in various parameters of flooding such as discharge, depth and inundation. They reported that the LULC changes from 1995 to 2005 show largest changes in flooding parameters, due to the massive loss in forest cover during the period, and LULC changes and its impact on flooding between 2005 and 2018 have not been as drastic as that between 1995 and 2005. Vishnu et al. (2019) used satellite-based data to map the flood inundation in the districts of Thrissur, Ernakulam, Alappuzha, Idukki and Kottayam. They used Sentinel-1A radar data of 21 August 2018 for a comparison with an average pre-flood, water-cover map based on Modified Normalized Difference Water Index (MNDWI) developed using a January and February 2018 Sentinel-2A dataset. They reported that low lying areas in the coastal plains of Kuttanad and the Kole lands of Thrissur had marked a rise of up to 5 and 10 m of water. Mishra and Nagaraju (2019) examined the Kerala floods of 2018 using satellite remote sensing data. They reported that Kerala received an excess of about

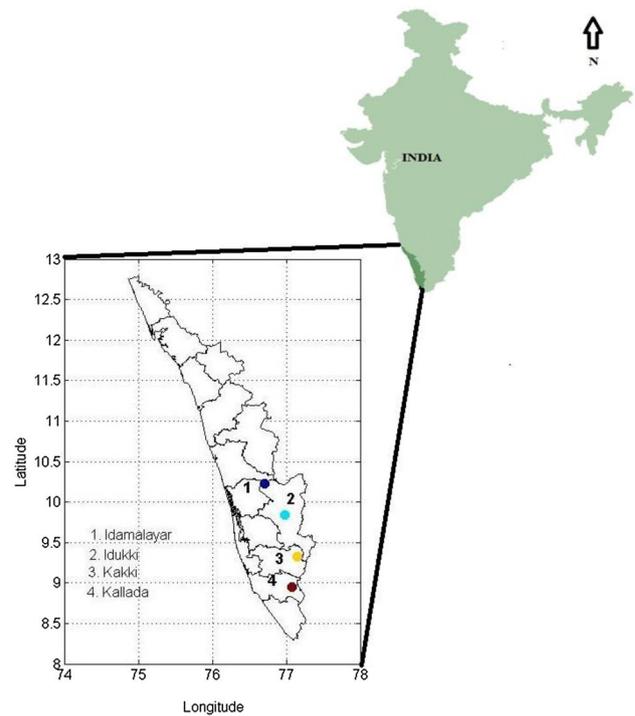


Fig. 1 Map showing the location of four major reservoirs in Kerala. **a** Idukki; **b** Idamalayar; **c** Kakki and **d** Kallada

56% rainfall during July and August from multi-day extreme rainfall episodes. It was highlighted that multi-day heavy rainy events during July and August brought an accumulated rainfall of about 1600 mm, which resulted in extreme flooding over Kerala. Ali et al. (2019) investigated the changes in the frequency of floods and associated risks under the warming climate in Indian sub-continent. Using downscaled and bias-corrected future and historic climate projections from Coupled Model Inter-comparison Project (CMIP5) and the Noah Multi-parameterization (Noah-MP) model, they showed that the frequency of single- and multi-day extreme precipitation and flood events is projected to increase substantially in the future over the Indian sub-continental river basins. It was also reported that the multi-day flood events are projected to increase with a faster rate in the future than the single-day events, which can have strong implications for agriculture and infrastructure, which is in line with the flood of 2018 and flood of 2019 happening now in Kerala. Joy et al. (2019) followed a participatory Geographic Information System (GIS) approach for flood plain mapping of Meloor panchayat in Thrissur district. Flood depth was surveyed and based on a GIS analysis, they reported that the flood height of some regions was up to 7.6 m and 53% of the study area was flood inundated.

Copulas (Nelsen 2007) are potential tools for investigating the joint dependencies of candidate variables in hydrological studies. Accordingly, the hydrological design tools

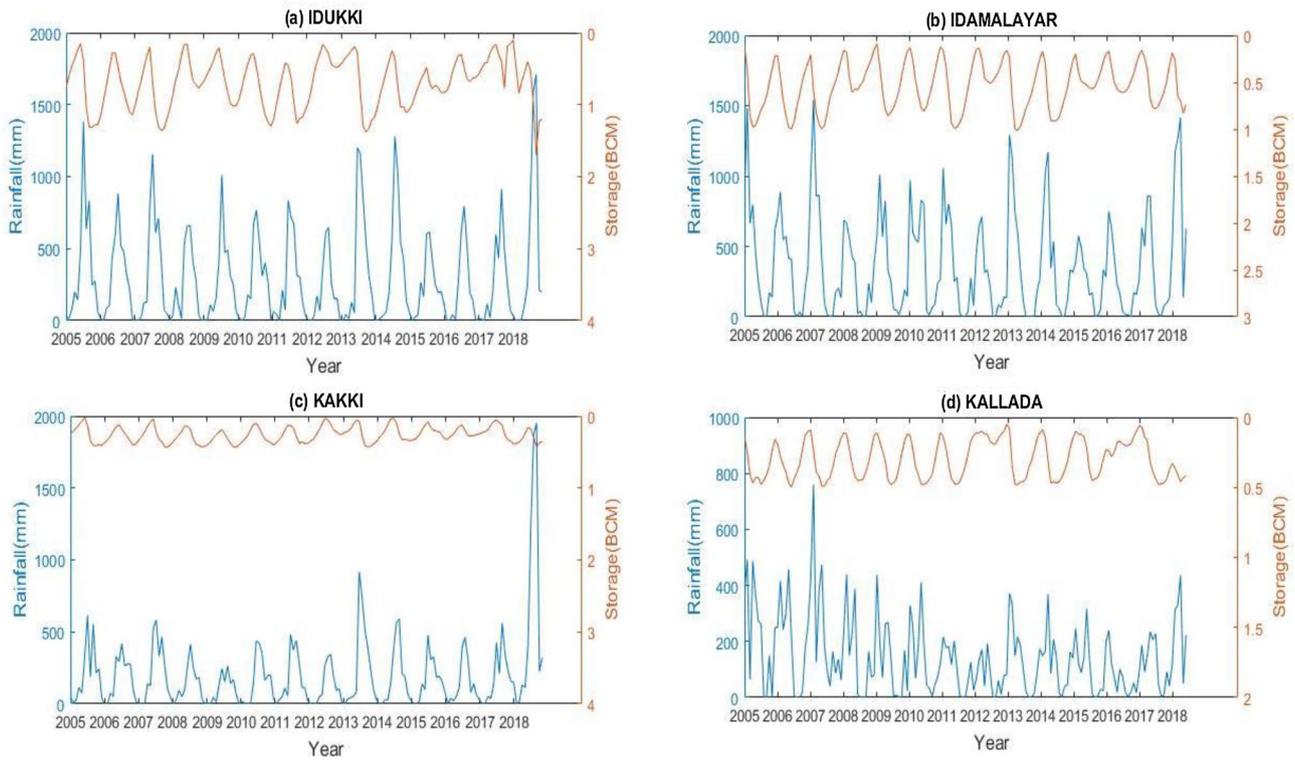


Fig. 2 Time series plots of rainfall and storage of four major reservoirs in Kerala. **a** Idukki; **b** Idamalayar; **c** Kakki and **d** Kallada

Table 1 Statistical properties of monthly storage and rainfall of four major reservoirs

Statistical property	Idukki		Idamalayar		Kakki		Kallada	
	Rainfall (mm)	Storage (BCM)						
Maximum	1710.00	1.38	1541.30	1.01	1953.00	0.43	760.00	0.50
Minimum	0.00	0.04	0.00	0.09	0.00	0.01	0.00	0.05
Mean	301.68	0.64	365.32	0.54	199.30	0.26	145.01	0.30
Standard deviation	344.84	0.36	360.17	0.26	271.24	0.11	137.80	0.14

are developed widely using this approach. For example, in flood frequency analysis (Zhang and Singh 2006; Salvadori and De Michele 2004; Karmakar and Simonovic 2009; Ganguli and Reddy 2013), developing drought-severity-duration-frequency curves (Shiau and Modarres 2009; Kao and Govindaraju 2010; Mirabbasi et al. 2012; Ganguli and Reddy 2012; Yusof et al. 2013; Adarsh et al. 2018). In addition to the above applications, the joint dependencies of hydro-meteorological variables have been also studied widely using Copulas (Singh and Zhang 2007; Ghosh 2010; Zhang et al. 2016; Pandey et al. 2018). It is well known that reservoir storage changes as a consequence of filling and emptying processes due to irregularity of precipitation and changes in the hydrological regime (Lopez-Moreno et al.

2004). Even though the highest level of reservoir storage is achieved by retaining the high flows in flood season, there exists a close and complex relationship between reservoir storage and precipitation, as the water demands for irrigation, power generation, water supply, ecological flow, etc. influence the storage-rainfall link. Zhang et al. (2016) investigated the joint dependencies between reservoir storage and different parameters such as upstream outflow and regional precipitation of two cascade reservoirs in a headwater basin of the Huaihe River, China in the context of drought occurrences. The results demonstrated that the probability of drought occurrences affected by both reservoir storage and precipitation/outflow is smaller than that by either of the variables. Investigating the concurrent effect of two extreme

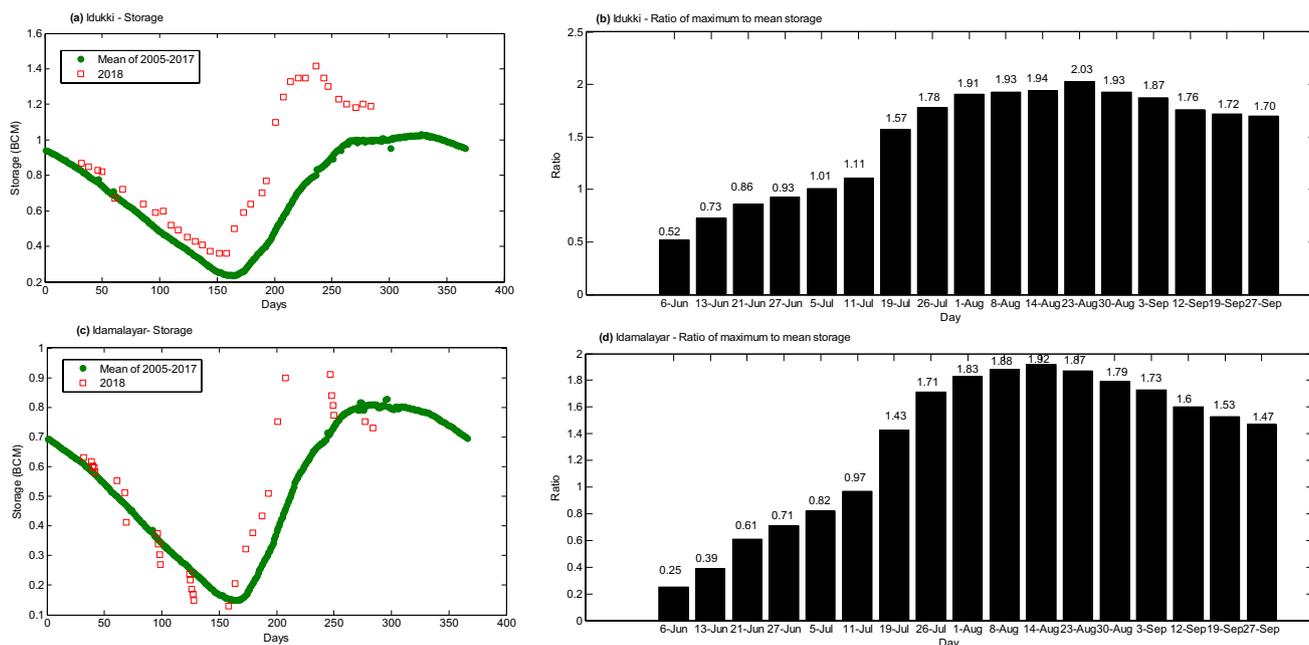


Fig. 3 Storage curves of Idukki and Idamalayar reservoirs. **a** Storage curve of Idukki reservoir; **b** ratio of maximum to mean storage of Idukki reservoir on different days of monsoon 2018; **c** storage curve

of Idamalayar reservoir; **d** ratio of maximum to mean storage of Idamalayar reservoir on different days of monsoon 2018

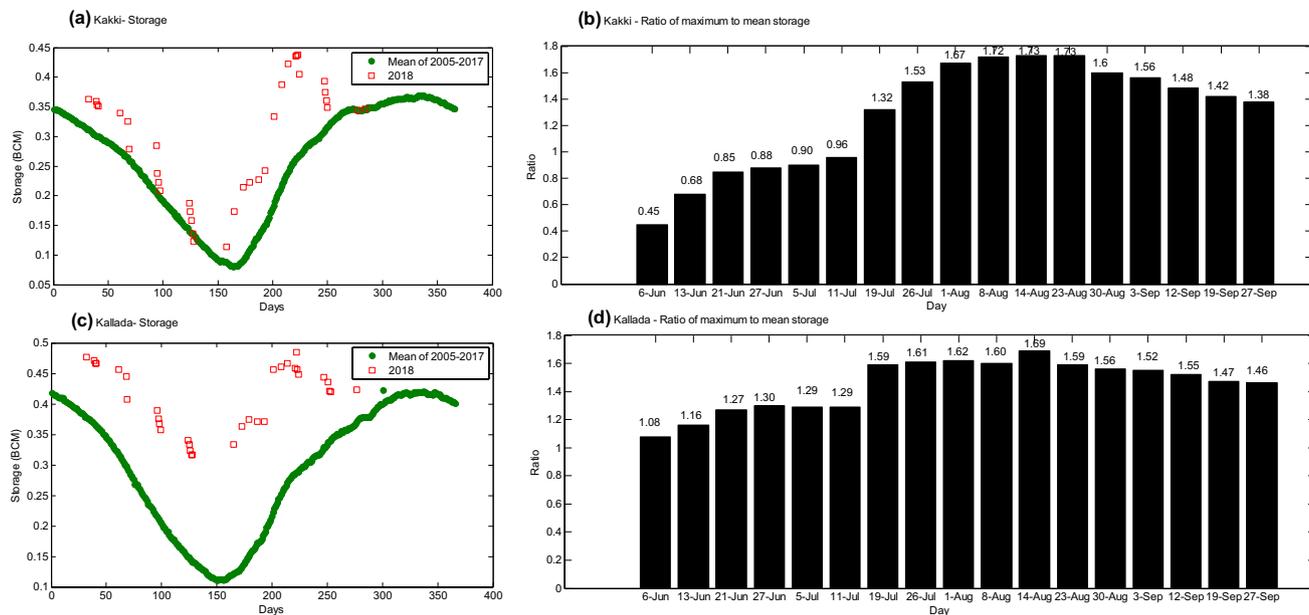


Fig. 4 Storage curves of Kakki and Kallada reservoirs. **a** Storage curve of Kakki reservoir; **b** ratio of maximum to mean storage of Kakki reservoir on different days of monsoon 2018; **c** storage curve

of Kallada reservoir; **d** ratio of maximum to mean storage of Kallada reservoir on different days of monsoon 2018

events is another emerging domain of research and the potential of Copulas has been successfully exploited for such studies (AghaKouchak et al. 2014; Hao et al. 2018). Zello and Rahali (2019) made a detailed investigation on the

combined effect and dependence between extreme rainfall and storm surge on the occurrence and severity of floods in the urban areas close to the estuary of the Bouregreg River (Morocco) using bivariate copula model. They reported that

Table 2 Spillway crest level (SCL) and full reservoir level (FRL) of different reservoirs (Source: KSEB Information centre, Vazhathope, Idukki)

Reservoirs	FRL (m)	SCL (m)	27–28 June 2018 (m)	26 July 2018 (m)	1–2 Aug 2018 (m)	7–8 Aug 2018 (m)	14–16 Aug 2018 (m)	22–23 Aug 2018 (m)	30 Aug 2018 (m)
Idukki	732.43	723.29	715.79	728.53	730.25	730.49	730.569	731.69	730.5
Idamalayar	169.00	161.00	143.44	164.9	167.03	168.06	168.71	167.76	166.38
Kakki	981.45	975.50	964.52	977.98	980.11	980.82	980.913	981.03	979.15
Kallada	115.82	106.73	110.60	114.79	115.02	114.65	115.72	114.52	114.07

The bold numbers indicate the storage levels above the spillway crest level

the joint probability of rainfall and tide both exceeding their critical thresholds remains low to moderate, and the biggest threat to this area might be caused by heavy rainfall. However, high tide adds an extra risk by reducing the capacity of the urban drainage in absorbing storm water; especially when rainfall intensity exceeds 100-year return period. In this study, the potential of Copulas is used for investigating the concurrent effect of extreme rainfall and reservoir storage on Kerala floods 2018.

The next section presents materials and methods used in the study. Section thereafter presents the data details. The subsequent section presents the results of storage analysis and Copula analysis along with discussions. The final section presents the major conclusions drawn from the study.

Materials and methods

This section presents the theoretical details of Copulas, which is the modeling tool used in this study.

Theory of Copulas

Copulas are joint distribution functions of standard uniform random variables. A bi-variate Copula can be represented as:

$$C[0, 1]^2 \rightarrow [0, 1]$$

It should satisfy the following conditions:

- (i) $C(1, u) = C(u, 1) = u$ and $C(u, 0) = C(0, u) = 0$;
- (ii) $C(u_1, u_2) + C(v_1, v_2) - C(u_1, v_2) - C(v_1, u_2) \geq 0$, if $u_1 \geq v_1, u_2 \geq v_2$ and $u_1, u_2, v_1, v_2 \in [0, 1]$. The Sklar's theorem (Sklar 1959) is the foundation of the theoretical concept of Copulas. A numerous families of Copula have been proposed over the years, which include (1) Elliptical (t and normal); (2) Archimedean (Clayton, Frank, Gumbel–Hougaard (GH), Ali-Mikhail-Haq); (3) Extreme Value (Gumbel, Galambos, Husler–Reiss, Tawn and t -EV); and (4) other families (Plackett and Farlie–Gumbel–Morgenstern). Among which, Archimedean Copula is more popular for hydrologic applications because of (1) easiness in its construction and implementation; (2) flexibility in application for both positively and negatively correlated variables; (3) availability of wide variety of formulations; and (4) uni-parameter property. In the present study, Frank, Clayton and Gumbel–Hougaard (GH) bivariate Copulas are considered. A detailed theoretical background on Copulas is presented by Nelsen (2007) and more details on statistical aspects of Archimedean family can be found in Genest and Rivest (1993).

Table 3 Best probability distributions of rainfall and storage data of the four reservoirs along with the distribution parameters

Reservoir	Best distribution	NLogL	BIC	AIC	Parameter/s
<i>Rainfall</i>					
Idukki	'Exponential'	1113.70	2232.00	2229.00	301.57
Idamalayar	'Exponential'	1111.02	2227.12	2224.04	365.31
Kakki	'Generalized Pareto'	1037.95	2091.24	2081.90	[0.32,138.53,- 2.22]
Kallada	'Exponential'	962.37	1930.00	1926.50	145
<i>Storage</i>					
Idukki	'Generalized Pareto'	51.92	119.17	109.84	- 0.85,1.18
Idamalayar	'Generalized Pareto'	- 14.23	- 13.22	- 22.46	[- 1.05,1.06]
Kakki	'Generalized Pareto'	- 180.63	- 345.93	- 355.27	[- 1.18,0.51]
Kallada	'Generalized Pareto'	- 135.25	- 225.26	- 264.51	- 1.16,0.52

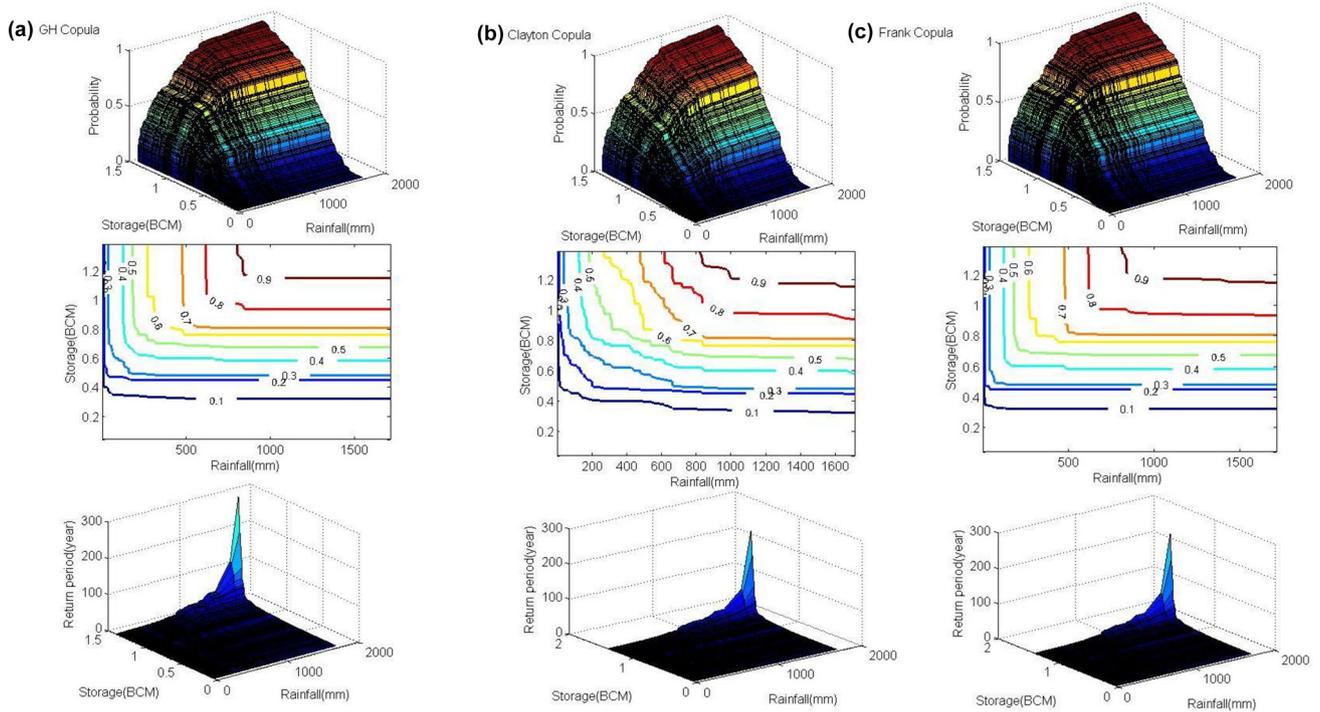


Fig. 5 Contours of joint probability, joint CDF and joint return period between storage and rainfall of Idukki reservoir using three Archimedean Copulas. **a** GH Copula; **b** Clayton Copula; **c** Frank Copula.

Upper panels show the surface plots of joint CDF; middle panels show the contours of joint probability; lower panels show the surface plots of joint return period

Methodology of analyzing joint dependencies using Copulas

The different steps involved in the study are:

1. Collect the monthly rainfall and reservoir storage data
2. Fit appropriate probability distributions for rainfall and reservoir storage data and develop their Cumulative Distribution Functions (CDFs)
3. Use Archimedean Copula to obtain joint CDF of rainfall and reservoir storage by estimating the Copula parameters
4. Determine the joint return periods of rainfall (R) and storage (S), which are defined for two cases: (1) T_{RS} , the return period for the case ($R \geq r$ or $S \geq s$) and (2) T'_{RS} , the return period for the case ($R \geq r$ and $S \geq s$).

The equations used in their estimation are:

$$T_{RS} = \frac{1}{P(R \geq r \text{ or } S \geq s)} = \frac{1}{1 - C(F_R(r), F_S(s))} \quad (1)$$

$$T'_{RS} = \frac{1}{P(R \geq r, S \geq s)} = \frac{1}{1 - F_R(r) - F_S(s) + C(F_R(r), F_S(s))} \quad (2)$$

The contour maps or surface plots can be used to demonstrate the joint return period for various rainfall and

storage. Another flexibility of Copula-based approach is its potential to provide conditional return periods, which have more practical appeal in preparing drought management plans and developing policies for the same (Mirabbasi et al. 2012).

5. Evaluate the conditional return period for rainfall and storage.

The conditional return periods are generally evaluated for two cases: (1) the recurrence interval of rainfall for the given condition that storage exceeds a specified threshold; and (2) the recurrence interval of storage given condition that the rainfall exceeds a specified threshold. In the Copula-based approach, the two cases of conditional return periods can be represented as:

$$T_{R/S \geq s} = \frac{T_S}{P(R \geq r, S \geq s)}, \quad (3)$$

$$T_{R/S \geq s} = \frac{1}{[1 - F_S(s)][1 - F_R(r) - F_S(s) + C(F_R(r), F_S(s))]} \quad (4)$$

$$T_{S/R \geq r} = \frac{T_R}{P(R \geq r, S \geq s)}, \quad (5)$$

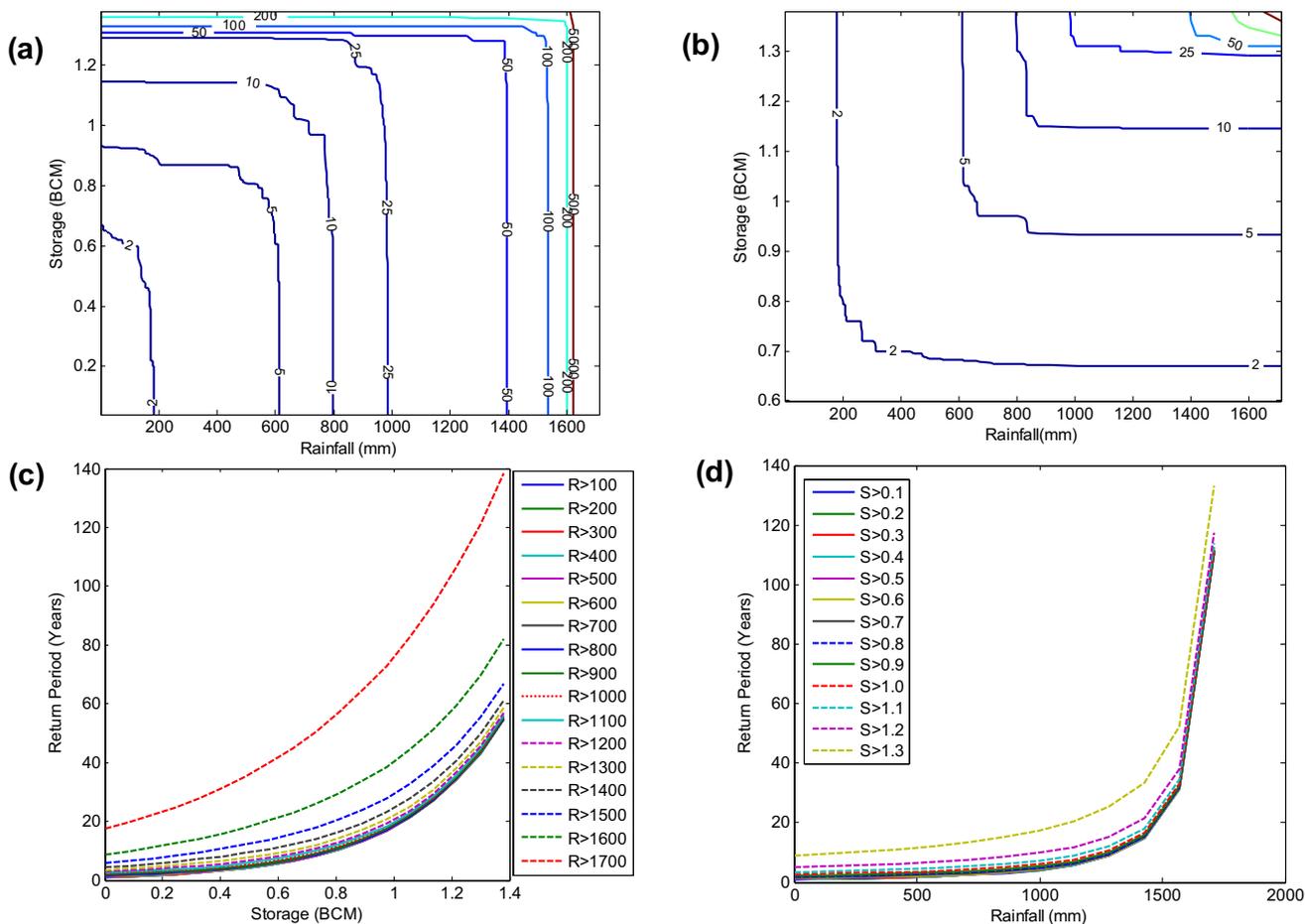


Fig. 6 The joint and conditional return periods for storage and rainfall of Idukki reservoir. **a** contours for the joint probability of storage and rainfall; **b** the joint return period between storage and rainfall

($R > r$; $S > s$); **c** conditional return period of storage given that rainfall exceeding certain threshold, $T_{S/R > r}$; **d** conditional return period of rainfall given that storage exceeding certain threshold $T_{R/S > s}$

$$T_{S/R \geq r} = \frac{1}{[1 - F_R(r)][1 - F_R(r) - F_S(s) + C(F_R(r), F_S(s))]} \tag{6}$$

where $T_{R/S \geq s}$ denotes the conditional return period for R given $S \geq s$; and $T_{S/R \geq r}$ represents the conditional return period for storage (S) for the condition $R \geq r$.

Study area and data

The highland physiography of Kerala state contains numerous dams and reservoirs which are predominantly designed for hydroelectric power generation as well as irrigation purposes. In this study, four major storage reservoirs in Kerala namely Kallada, Kakki, Idukki and Idamalyar which are having no trans-boundary water sharing issues are considered, and these reservoirs filled about 90% of FRL storage in August 2018 (Mishra et al. 2018). The monthly rainfall and storage for 2005–2018 period are used for the analysis. The map showing the location of the

reservoirs is presented in Fig. 1. The data of rainfall and storage of the four reservoirs are presented in Fig. 2 and from the plot it is very clear that the maximum rainfall and storage are inextricably linked. The statistical properties of the data are presented in Table 1.

Idamalyar experienced high rainfall of about 1500 mm in 2007 which is more than that of the maximum rainfall of 1200 mm received during the monsoon of 2018. Idukki and Kakki experienced the maximum rainfall in 2018 August and it is about 1700 mm and 1953 mm, respectively. In the above three cases, monthly storage has not much variation. In the case of Kallada, there is not much variation for rainfall as well as storage and the maximum rainfall is about 760 mm. In short, at Kakki and Idukki reservoirs, the maximum monthly rainfall was noted in 2018; whereas, the maximum monthly rainfall of Idamalyar and Kallada reservoirs received in 2007. From the datasets, it can be inferred that the rainfall might have played a dominant role on flood 2018 in some of the reservoirs like Idukki and Kakki.

Table 4 Identification of the best Copula for the data of four reservoirs in Kerala

Copula type	AIC	BIC	Copula parameter
<i>Idukki</i>			
GH	- 5363	- 5360	2.69
Clayton	- 4695	- 4692	0.17
Frank	- 4869	- 4866	13.72
<i>Idamalayar</i>			
GH	- 4986	- 4983	2.12
Clayton	- 4666	- 4663	0.17
Frank	- 5013	- 5010	14.55
<i>Kakki</i>			
GH	- 4215	- 4212	1.16
Clayton	- 4421	- 4418	0.13
Frank	- 4642	- 4639	15.86
<i>Kallada</i>			
GH	- 4795	- 4792	2.36
Clayton	- 4173	- 4170	0.13
Frank	- 4981	- 4978	23.76

The values in italics refer the best Copula fit

Results and discussion

This section presents the results of reservoir storage analysis and Copula-based modeling used for investigating the concurrent impact of extreme rainfall and reservoir storage on the Kerala flood 2018.

Reservoir storage analysis

As a preliminary analysis, the storage data of the four reservoirs were statistically analyzed. The storage volume curves of the four reservoirs are prepared and presented in Figs. 3 and 4, respectively. From Figs. 3 and 4, it is noted that the storage of 2018 was above the mean storage in all reservoirs, in most of the days of the monsoon period of 2018; while, it is completely above the mean at Kallada reservoir. The ratio of the maximum to mean storage of different reservoirs is also presented in these figures. The graphs showed that Kerala received above normal rainfall in the monsoon season of 2018. Many of the major reservoirs in Kerala except Periyar had 90% of its full capacity during flood (Mishra et al. 2018). The reservoir storage of Idamalayar, Idukki and Kakki was above average in June–July and reached peak value by the end of July and beginning of August.

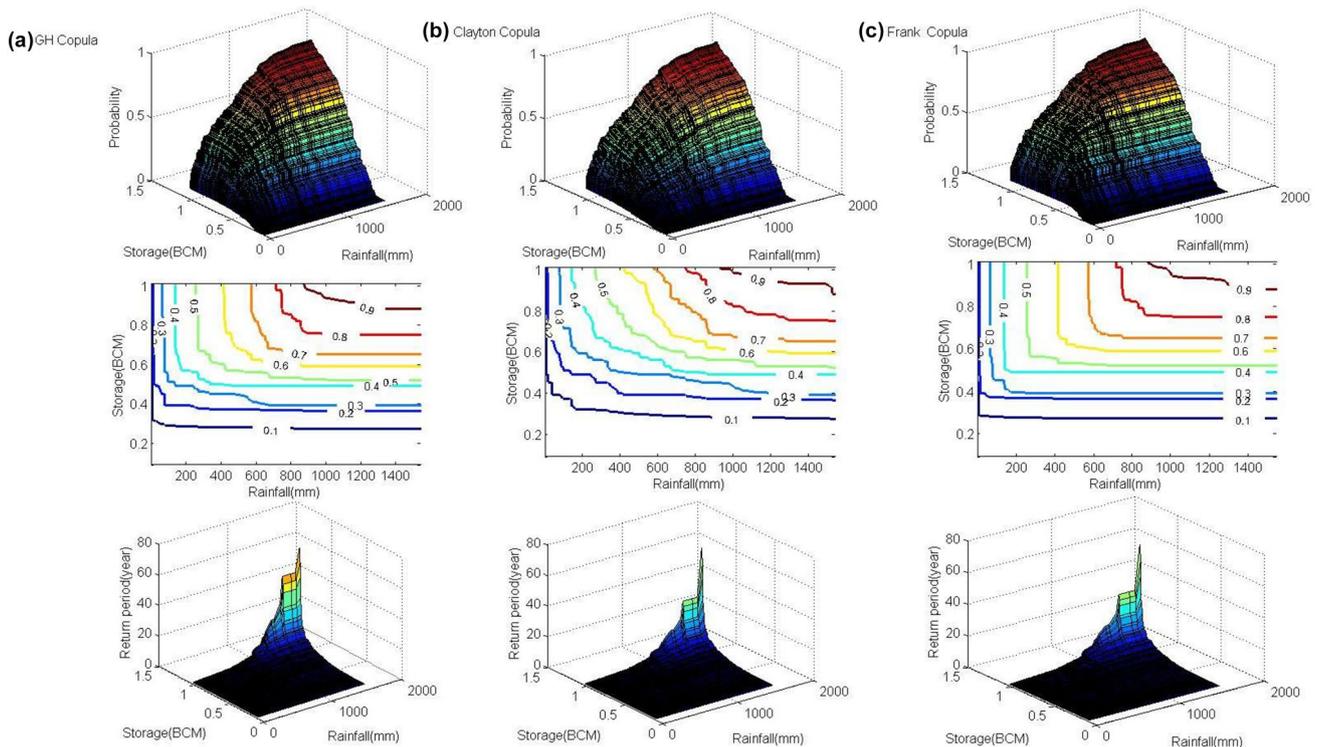


Fig. 7 Contours of joint probability, joint CDF and joint return period between storage and rainfall of Idamalayar reservoir using three Archimedean Copulas. **a** GH Copula; **b** Clayton Copula; **c** Frank

Copula. Upper panels show the surface plots of joint CDF; middle panels show the contours of joint probability; lower panels show the surface plots of joint return period

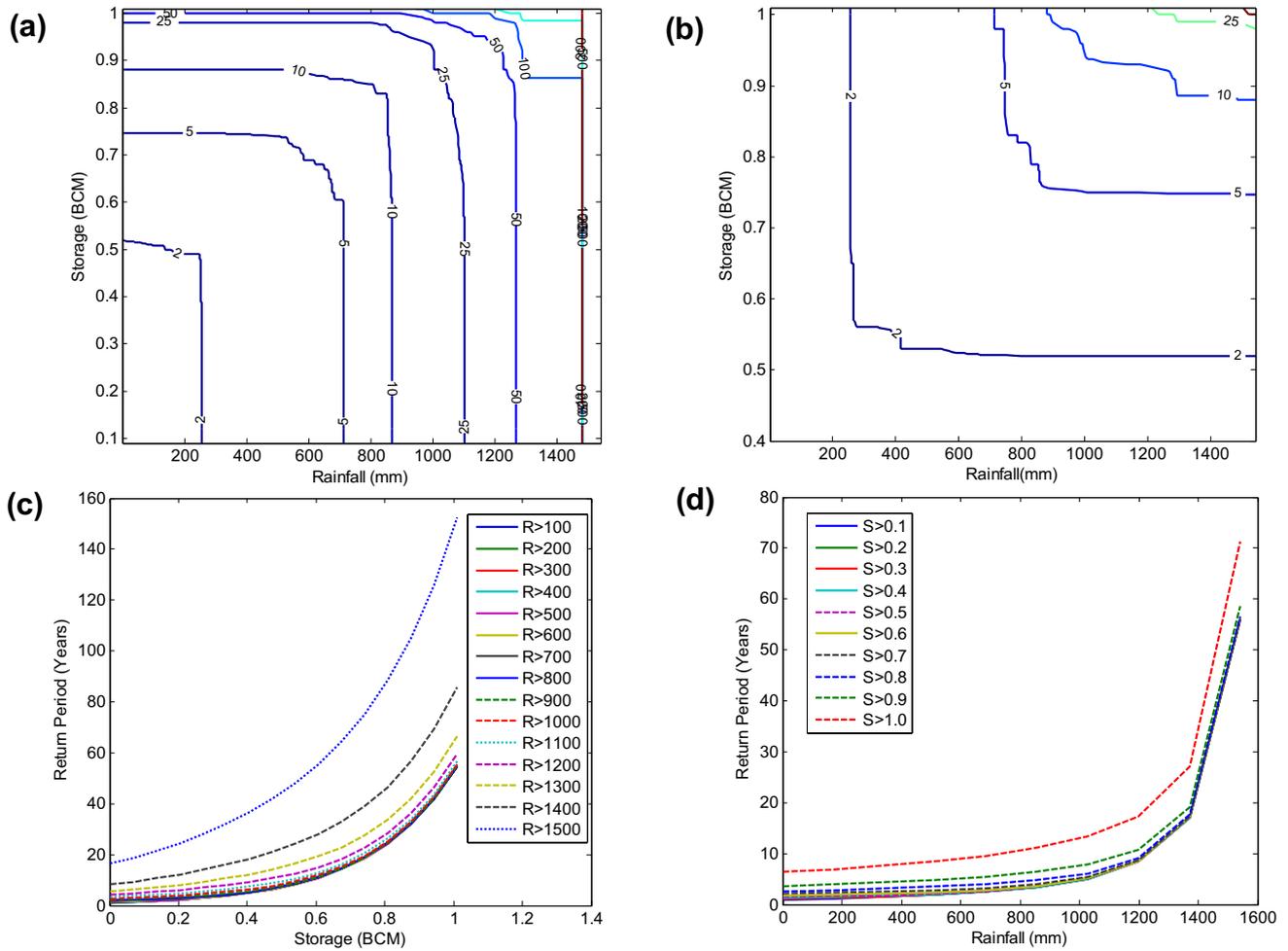


Fig. 8 The joint and conditional return periods for storage and rainfall of Idamalayar reservoir. **a** Contours for the joint probability of storage and rainfall; **b** the joint return period between storage and rainfall

($R > r$; $S > s$); **c** conditional return period of storage given that rainfall exceeding certain threshold, $T_{S/R > r}$; **d** conditional return period of rainfall given that storage exceeding certain threshold $T_{R/S > s}$

Historical rainfall data of the Kerala state indicate that maximum rainfall is experienced during the month of June and July when compared to August and September. But during August 2018, Kerala experienced the most severe extreme rainfall events on record. On an average, Kerala received above normal monsoon rainfall from 1st June 2018 to 19th August 2018, which is roughly 42% above normal rainfall for the same period. According to Sudheer et al. (2019), rainfall magnitude of rainfall in June 2018 had a return period of only 3 years and rainfall in July 2018 had a recurrence interval of 8 years, but the rainfall in August was found to be 145 years of return period. The heavy rainfall in the upstream catchments was unprecedented and it has contributed to the reservoir storage significantly. It resulted in the rising of water level near FRL of the reservoir and it had to release significant amount of water in a short span of time. The spillway crest level, Full Reservoir Level (FRL) and the water level of four

reservoirs in different days of the monsoon 2018 period are presented in Table 2. From Table 2, it is noted that the water level in all the four reservoirs crossed the spillway crest level by July 26, 2018 and the water level displayed a consistent increase in the month followed and the trend is very much evident. One cannot ignore the fact that most of the dams in Kerala are primarily designed for the hydroelectric power generation as well as irrigation purposes and not for the flood control. Therefore, the operation policy has been to maintain the reservoir storage close to FRL throughout the monsoon to ensure maximum power generation. By 22nd August, the water level became close to FRL in most of the reservoirs (about 90% of FRL) and this made the situation challenging to manage and the release resulted in flood damage in most of the districts in Kerala. It is true that the situation was extra ordinary in August 2018, even though the water level could have stored up to FRL considering the power generation and downstream

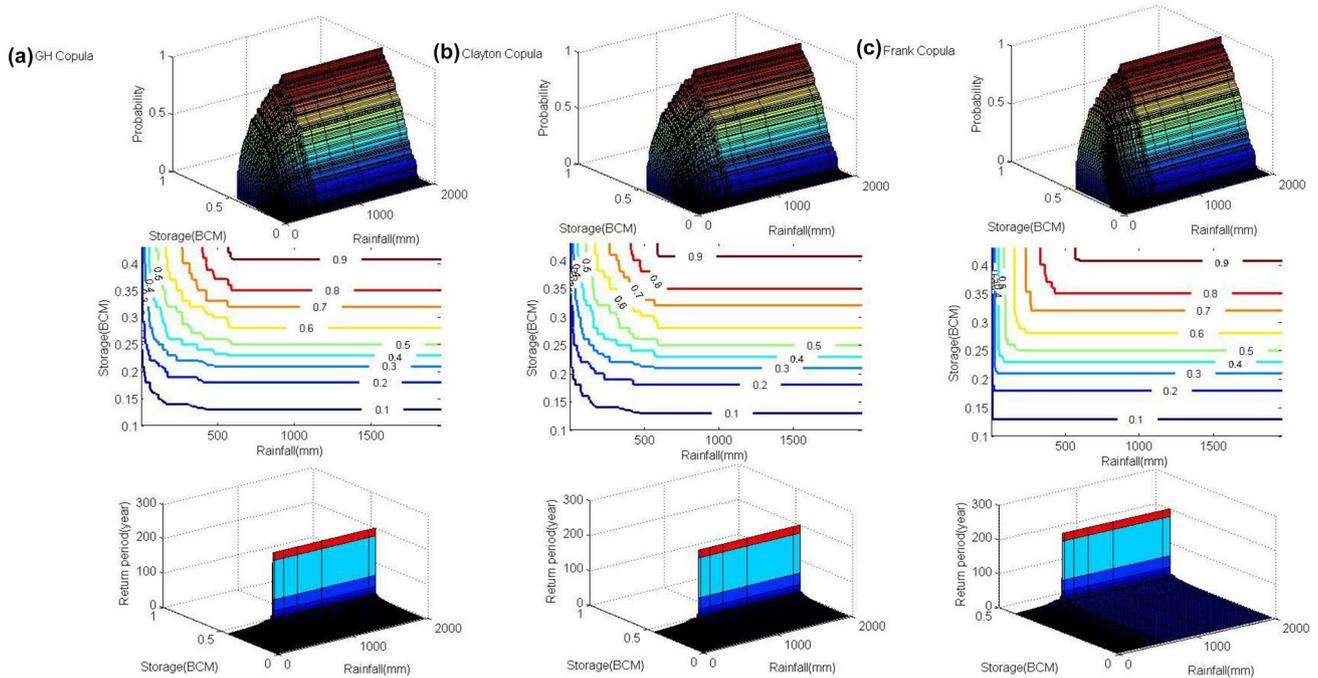


Fig. 9 Contours of joint probability, joint CDF and joint return period between storage and rainfall of Kakki reservoir using three Archimedean Copulas. **a** GH Copula; **b** Clayton Copula; **c** Frank Copula.

Upper panels show the surface plots of joint CDF; middle panels show the contours of joint probability; lower panels show the surface plots of joint return period

channel capacity. But the possibility of early and systematic release based on the increasing trend in the storage level could have a plausible management option. This might have attenuated the flood peaks and played a role in alleviating the flood damage at downstream reaches.

Copula-based modeling

Joint probabilities of rainfall characteristics and reservoir storage are important for flood management. Joint and conditional return periods of flood can be used by water resources managers and engineers as a hydraulic design criterion and provide useful information for evaluating risk. The first step in modeling bivariate distribution using Copulas is to obtain the marginal distributions. For fitting marginal distribution of monthly rainfall and reservoir storage data of each reservoir, we tried 16 different candidate probability distributions (such as exponential, generalized Pareto, log normal, gamma, Weibull). The selection of best probability of each case is done statistically using the Akaike Information Criteria (AIC) and Bayesian Information Criteria (BIC) by selecting the minimum of AIC (or BIC) among the different candidate distributions. For brevity, the value of parameters of the best distribution and the value of selection criteria only are provided in Table 3. It is noted that for Idamalayar, Idukki and Kallada reservoirs, exponential distribution appears to be the best fit for monthly rainfall data, and it is

generalized Pareto for Kakki reservoir. For the storage data of the above four reservoirs, generalized Pareto distribution is obtained as the best fit. The best distribution is used for developing the marginal CDFs of rainfall and storage of each case. After identifying the best marginal distribution, three different Archimedean Copulas—Gumbel–Hougaard (GH), Clayton and Frank are used for deriving the joint CDFs. Subsequently, the surface plot of joint CDF and the contour plot of joint probabilities are developed for the dataset of each reservoir. Then using the basic formula (Eq. (1)), the return periods are determined. Contours of joint probability, joint CDF and joint return period between storage and rainfall of Idukki reservoir using three Archimedean Copulas are shown in Fig. 5. In this case, the maximum joint return period is found to be 289 years. The best Copula is used for developing the contour plots of joint return period and conditional return periods and the results are presented in Fig. 6. The Copula parameter and the AIC (and BIC) statistics of the three Copulas for all the four reservoirs are summarized in Table 4. From the analysis, it is noted that for Idamalayar, Kakki and Kallada reservoirs, Frank Copula is obtained as the best fitted Copula; whereas for Idukki reservoir, the GH Copula is identified as the best fitted Copula. The larger the bivariate joint return period implies a smaller probability of simultaneous occurrence of reservoir storage and rainfall. The threshold of rainfall is considered at an interval of 100 mm and that of storage is considered at an interval

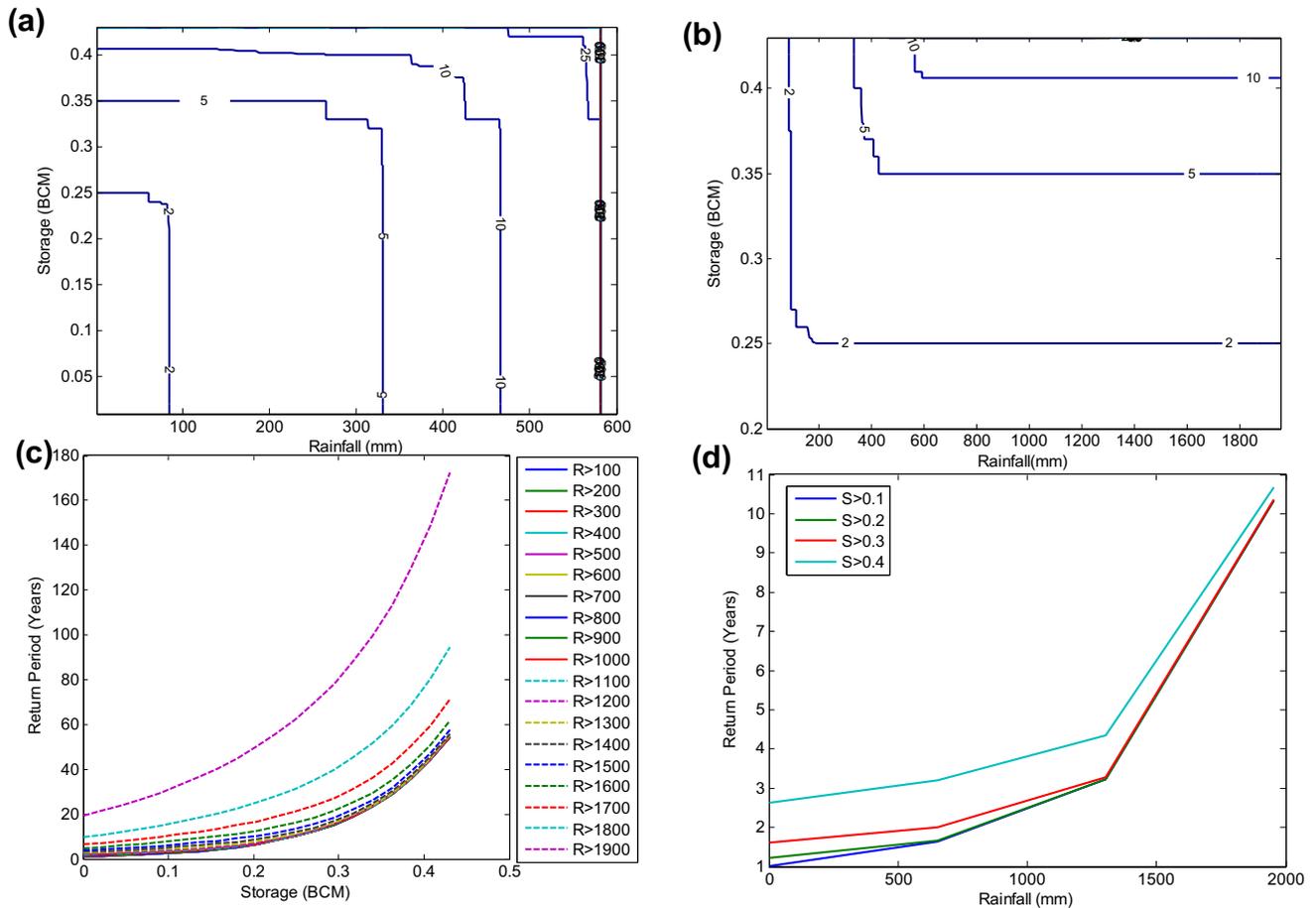


Fig. 10 The joint and conditional return periods for storage and rainfall of Kakki reservoir. **a** Contours for the joint probability of storage and rainfall; **b** the joint return period between storage and rainfall

($R > r$; $S > s$); **c** conditional return period of storage given that rainfall exceeds certain threshold, $T_{S/R > r}$; **d** conditional return period of rainfall given that storage exceeds certain threshold $T_{R/S > s}$

of 0.1 BCM. The probability that both the rainfall and the storage simultaneously exceed certain thresholds is useful information for environmental and government agencies for improving management of hydrosystems under flood condition. Conditional distributions can be easily derived from the Copula-based bivariate distribution, which may help to evaluate the risk under multiple combinations of extreme rainfall and reservoir storage. There is an upward shift in the curves corresponding to the increase in threshold rainfall magnitude; this difference is marginal for the low values of rainfall. For the highest threshold rainfall of 1700 mm, the curve of return period appears at the top. There is a visible change in the conditional return period curve of storage from the threshold rainfall of 1200 mm.

For Idamalayar reservoir, after identifying the best marginal fits (exponential for rainfall and generalized Pareto for storage), Frank, Clayton and GH Copulas are used for deriving joint distributions. The joint return period curves are prepared and the surface plot of the same is presented in Fig. 7 and the maximum joint return period is found to be

68 years in this case. The Frank Copula is identified to be the best in this case and the conditional return period curves are derived for two cases based on Eqs. (4) and (6). The contours of joint and conditional return periods are presented in Fig. 8. Figure 8c shows that the difference between the curves is marginal up to a threshold rainfall of 1100 mm and for subsequent increments, the difference increases.

Unlike the other two reservoirs, in the case of Kakki reservoir, the generalized Pareto distribution is found to be fitting best for both rainfall and reservoir storage. Even though Copula approach is more suitable for the joint dependency of variables with two different marginal distributions, the same approach is followed for getting the joint dependency structure between rainfall and reservoir storage, as the Copula approach is a generalized case. The surface plots of joint CDF and joint return periods are presented in Fig. 9. Subsequently, the best fitted Frank Copula is used for developing the plots of joint and conditional return periods and the results are presented in Fig. 10. Figure 10c shows that the difference between the curves is more perceptible for

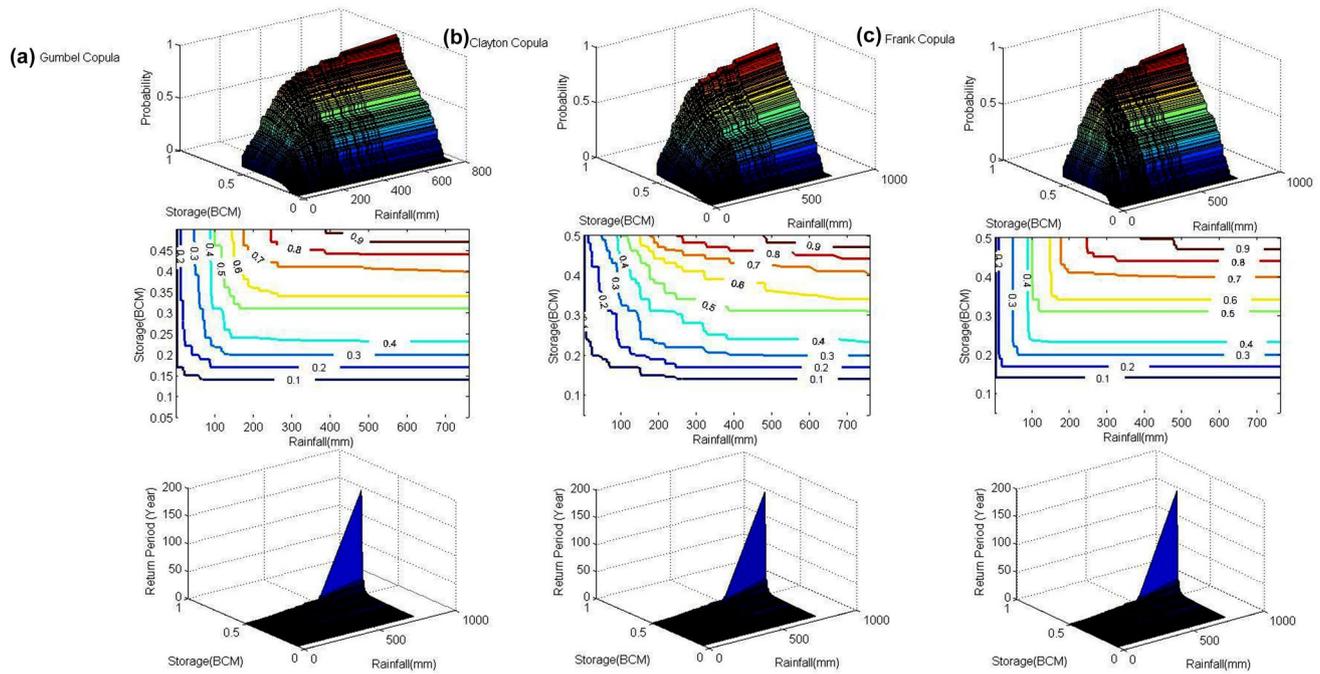


Fig. 11 Contours of joint probability, joint CDF and joint return period between storage and rainfall of Kallada reservoir using three Archimedean Copulas. **a** GH Copula; **b** Clayton Copula; **c** Frank

Copula. Upper panels show the surface plots of joint CDF; middle panels show the contours of joint probability; lower panels show the surface plots of joint return period

a threshold rainfall of 1500 mm. For the data of Kallada reservoir, identical procedure is followed to derive the joint and conditional return period curves. The surface plots show that the maximum joint return period is 148 years and for the conditional return period plot displays a drastic change only for rainfall exceeding 700 mm. The results of Copula analysis of Kallada reservoir are provided in Figs. 11 and 12.

Sensitivity of maximum joint return period

To investigate the influence of extreme rainfall, the joint return periods are separately determined for rainfall series of three different time spells 2005–2010, 2005–2015 and 2005–2018. The results of maximum joint return period and maximum rainfall are summarized in Table 5.

The return period of the joint effect of rainfall and storage on Idamalayar is obtained as 68 years for the third time spell, against 56 years and 75 years in the first two time spells. The maximum rainfall of 1541 mm is found to be in the first spell itself and the variation in the joint return period is relatively less, as the rainfall in August 2018 was not the extrema. In the case of Idukki and Kakki reservoirs, large joint return period (289 and 200 years, respectively) is noted at the time of 2018 Flood when the rainfall is maximum (1710 mm and 1953 mm, respectively). In these two cases, the magnitude of joint return period is mainly decided by the magnitude of rainfall.

The maximum joint return period is about 2.8 times, 2.33 times that of the value of 2005–2015 spell, respectively, for Idukki and Kakki reservoirs. In the case of Kallada reservoir, the maximum rainfall of 760 mm is reported to be in 2007 (in the first time spell), which might have resulted in a lesser impact on the maximum joint return period value of 188 years in the third time spell against 141 years in the second time spell.

This study presented an alternate way of investigating the concurrent impact of the extreme rainfall and reservoir storage on the devastating flood happened in the state of Kerala in 2018.

The estimated curves of conditional and joint probability offers useful information in the estimation of flood risk associated with the structures for many combinations of rainfall and storage. This may eventually help the water resources planners and managers for framing plausible changes in the operational policies of the reservoirs.

Conclusions

The Kerala flood 2018 was unprecedented and the rare combination of the occurrence of the extreme rainfall events along with storage near FRL of different reservoirs made the management challenging. This study presented the analysis of storage of four major reservoirs and the dependency

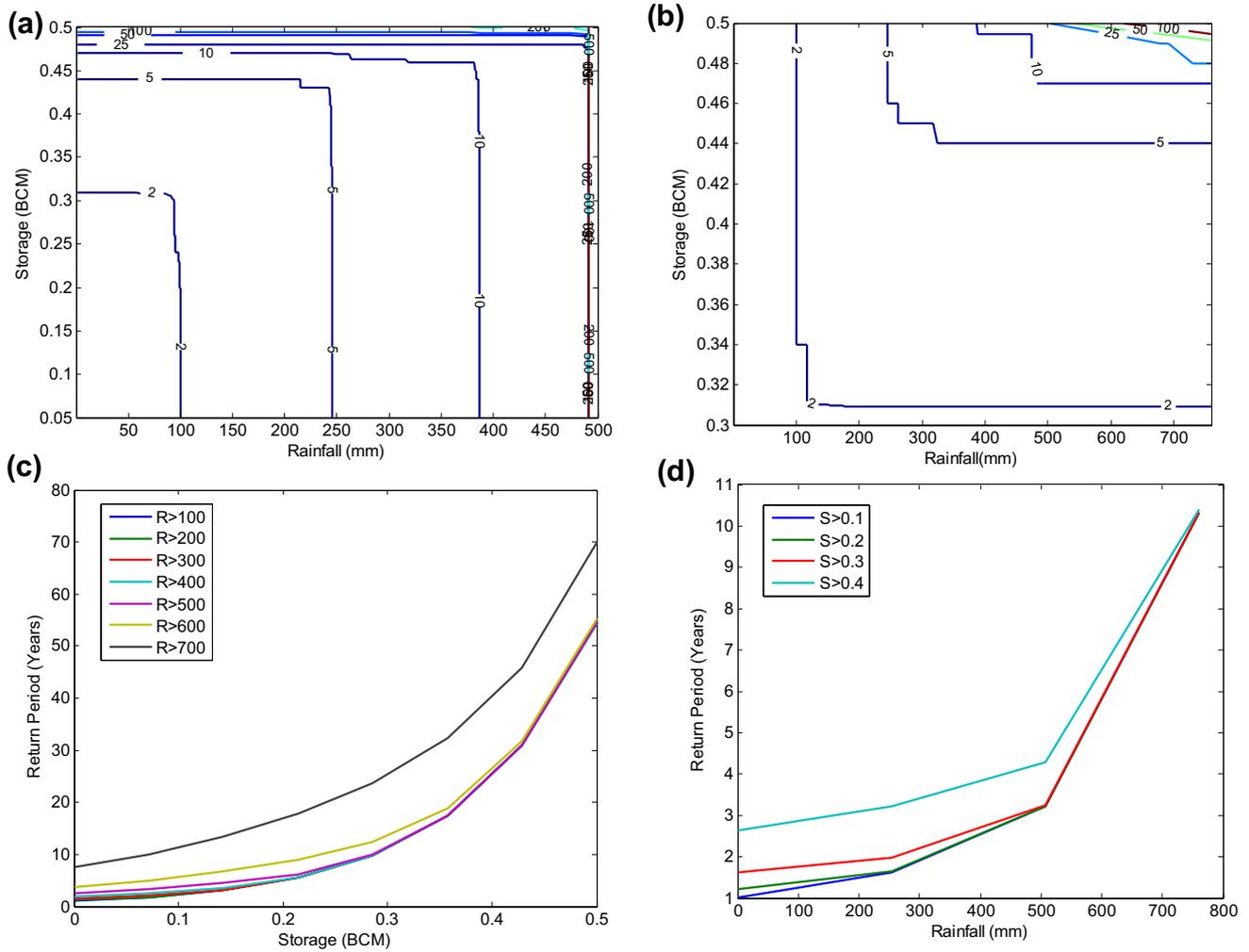


Fig. 12 The joint and conditional return periods for storage and rainfall of Kallada reservoir. **a** Contours for the joint probability of storage and rainfall; **b** the joint return period between storage and rainfall ($R > r; S > s$); **c** conditional return period of storage given that rainfall exceeds certain threshold, $T_{S/R>r}$; **d** conditional return period of rainfall given that storage exceeds certain threshold $T_{R/S>s}$

Table 5 Maximum rainfall and joint return period

Time period	Idamalayar		Idukki		Kakki		Kallada	
	Max. return period (years)	Max. rainfall (mm)	Max. return period (years)	Max. rainfall (mm)	Max. return period (years)	Max. rainfall (mm)	Max. return period (years)	Max. rainfall (mm)
2005–2010	56	1541.3	96	1382	52	615	52	760
2005–2015	75	1541.3	102	1382	97	917	141	760
2005–2018	68	1541.3	289	1710	204	1953	188	760

structure of the reservoir storage and extreme precipitation to get an insight into the concurrent impact of the two prominent reasons of flood damage of Kerala in 2018. The bivariate Copula-based analysis is used to derive the joint distribution and conditional return period of Idukki, Idamalayar, Kakki and Kallada reservoirs in Kerala. From the

analysis of reservoir storage and the Copula-based analysis on concurrent effect of storage and rainfall, the following conclusions are drawn:

- In all reservoirs, the storage level crossed the spillway crest level by July 26 2018 and most of the reservoirs

filled up to 90% at the end of July 2018 during the flood. From the storage levels and spillway crest levels of different reservoirs, it is inferred that the controlled release considering the trend in reservoir levels might have helped in mitigating the flood. Exploring the possibility of early and systematic release based on the increasing trend in the storage level could have a plausible management option.

- The best fit Copula for Idukki data is Gumbel–Hougaard and it is Frank for the data of other three. The maximum joint return period obtained as 289, 204, 188 and 68 years for Idukki, Kakki, Kallada and Idamalayar, respectively.
- Idukki and Kakki reservoirs experienced extreme rainfall in 2018 and effect of extreme rainfall might be a dominant factor for flood in these reservoirs.

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