

Role of dams on the floods of August 2018 in Periyar River Basin, Kerala

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Kerala state (India) experienced a devastating flood event during the month of August 2018. While an extreme rainfall event (ERE) was the primary reason for this flood, there was criticism at various levels that the authorities failed to manage the flood effectively through reservoir operations. One of the worst affected basins, Periyar River Basin (PRB), received a 145 year return period rainfall. This study reports the results and analysis of a modelling exercise using HEC-HMS to simulate and analyse the role of dams, as well as reservoir operations, on the flood of August 2018. The results indicated that the role of releases from the major reservoirs in the PRB resulting in the flood havoc was less. The analysis suggested that reservoir operations could not have helped in avoiding the flood situation as only 16–21% peak attenuation was possible by emptying the reservoir in advance, as the bulk of runoff to the flooding was also contributed by the intermediate catchments without any reservoirs to control. Further, the attenuated flood peak due to advance emptying of the reservoir would still be almost double the safe carrying capacity of the river section at Neeleswaram. In addition, the reliability of the rainfall forecast at higher lead times is also a concern for the reservoir operation. It is noted that the probability of EREs of this kind in the month of August in PRB is very small (0.6%), and therefore any planned operation could not have helped in mitigating floods of such magnitude without a reliable EREs forecast coupled with reservoir inflow forecasting system and optimized set of reservoir operational policies.

Keywords: Extreme rainfall events, HEC-HMS, Kerala flood 2018, Periyar River Basin, reservoir operation.

EXTREME rainfall events (EREs) and associated floods causing substantial damage to mankind, infrastructure, and the physical environment are a subject of global concern^{1–3}. India has witnessed severe floods in the last two decades owing to EREs, among which the prominent ones are the events which occurred in Mumbai (Maharashtra in 2005), Kosi (Bihar in 2008), Krishna (Andhra Pradesh in

2009), Leh and Ladak (Jammu & Kashmir in 2010), Kedarnath (Uttarakhand in 2013) and Chennai (Tamil Nadu in 2015). The extent of human and livestock mortalities, crop damages and economic losses due to the floods was enormous (www.ndma.gov.in/en/disaster-data-statistics.html). The total estimated loss due to the damages incurred during floods in India between 1953 and 2016 was estimated to be approximately INR 347,581 crores (www.cwc.gov.in/main/downloads/state-wiseflood_data_damage_statistics.pdf).

During August 2018, Kerala state (India) experienced some of the most severe EREs on record. This resulted in extensive flooding and landslides across most districts of the state, causing severe damage to both the built and natural ecosystems. According to the India Meteorological Department (IMD), the occurrence of the EREs in August 2018 was mainly due to formation of monsoon depressions over the Bay of Bengal and the west-northwestward movement of the depression over coastal Odisha and neighbourhood (www.imd.gov.in/pages/press_release.php dated 23 August 2018). On an average, Kerala received significantly high Indian summer monsoon rainfall (ISMR) from 1 June 2018 to 19 August 2018 (2346.6 mm), which is roughly 42% above the normal rainfall for the same period. Among the different districts of the state, Idukki received the maximum rainfall, which was almost 100% excess compared to the normal rainfall (3555 mm against the normal 1852 mm). During the first 19 days of August 2018, Kerala received 164% above normal rainfall, of which the major share was from two EREs during 8–10 and 14–19 in August 2018. The two rain gauge stations that realized maximum cumulative rainfall during 15–17 August 2018 was Peerumedu (>800 mm) and Idukki (>700 mm)⁴, both belonging to Idukki district in the Western Ghats. The highland physiography of Kerala supports numerous dams and reservoirs, which are predominantly designed for hydroelectric power generation as well as irrigation purposes. The state has experienced the onset of monsoon in the beginning of June 2018, and by the end of July 2018 most of the reservoirs in the state were almost near FRL^{4,5}. This rare combination of the occurrence of the EREs, along with near full reservoir level (FRL) reservoir storages, made the

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situation challenging and compelled the authorities to open the gates of most of the dams in the state, which resulted in severe flooding in 13 out of 14 districts of the state⁴. The extent of damage due to this flooding was preliminarily estimated to be to the tune of INR 20,000 crores⁶. In addition, a loss of about 55,000 ha of agricultural land was also estimated as caused by the flood.

The role of dams and its operations in causing/mitigating the flood have been criticized and debated in the scientific, social and political contexts, and the discussions, though mixed, explicitly held that the reservoir operations practiced during the flood and the lack of adequate warnings were responsible for the paroxysm (www.thehindu.com/sci-tech/energy-and-environment/reservoirs-not-managed-using-a-scientific-decision-support-system-m-rajeevan/article24785253.ece; www.thehindubusinessline.com/opinion/dams-did-exacerbate-keralas-floods/article24988070.ece). The study⁵, based on the analysis of the IMD gridded rainfall data ($0.25^\circ \times 0.25^\circ$) for the period 1901–2018 and reservoir storage information for seven major reservoirs of the state from India Water Resources Information System (WRIS) for the period 2007–2018 suggested that above normal seasonal rainfall (since 8 August 2018), maximum reservoir storage (~90% of the FRL) prior to the EREs, and EREs in the upstream catchment areas of the reservoirs have worsened the flooding in Kerala. Central Water Commission (CWC, India) in its rapid assessment of the flooding situation in Kerala⁴ indicated that the reservoir releases during the ERE could not have been avoided as most reservoirs were near FRL, and the reservoir releases did not play any role in the extent of the flooding situation. The inference by CWC⁴ was based on the total quantum of flood generated to the storage capacity of the reservoirs, whereas the inference by the study⁵ was based on the observed record of reservoir storage. In both these studies, numerical simulation of floods under different reservoir storage scenarios has not been attempted. Hence, one main question remains unexplained: whether the early release of the water stored in the reservoirs would have attenuated the flood peaks, and if so, what would have been the extent of this attenuation? It is important to answer this question to (i) evolve a better policy for operating these reservoirs in the future and (ii) to find ways to minimize the flooding damage caused by EREs in this region.

Consequently, a hydrologic modelling based approach was used in this study to answer the above question in the backdrop of the flood events that occurred during August 2018. One of the major river basins that was severely affected by the 2018 flood in Kerala state was the Periyar River Basin (PRB), and the present study investigates the role of dams, as well as reservoir operations, in causing the flood in PRB. Periyar river system is regulated by 17 dams/barrages and reservoirs, and 80% of the hydroelectric projects of the state are located in the basin⁷. The

flood events that occurred in PRB during August 2018 were numerically reconstructed in this study, and different scenarios of reservoir operation and antecedent conditions were analysed using the Hydrologic Modelling System of Hydrologic Engineering Centre, US Army Corps of Engineers (HEC-HMS).

Materials and methods

Periyar River Basin

The state of Kerala is located on the southernmost part of the west coast of India and is confined between the Western Ghats in the east and the Arabian Sea in the west. The state is unique as the onset of the ISMR normally starts over the Kerala coast, and the state belongs to one of the highest monsoon rainfall regions in India, along with the northeast India. The annual normal rainfall of the state is around 3000 mm with significant spatial variability across the state, and June and July months contribute the dominant share to the annual rainfall (~50%)^{8,9}. Topography of Kerala shows wide diversity ranging from rugged and undulating highlands to gentle coastal plains, and the width of the state (i.e. mostly the distance between the ridgeline of the Western Ghats and the coastal line) varies between 15 and 120 km. The gentle coastal plains of the state are densely populated, and the midland and the highland zones are predominantly utilized for various agricultural activities and commercial plantations. The narrow width of the state between the ridgeline of the Western Ghats and the coastal line along with dense population means, that the river basins have shorter response time to EREs and hence prone to severe flooding.

Periyar is the longest river in Kerala (244 km), and PRB is the second largest river basin of Kerala, with a catchment area of 5398 sq. km, and drains parts of Idukki and Ernakulam districts of the state (Figure 1). The basin has an inverted 'L' shape with a maximum width at the intersection. Major tributaries of the river are Mullayar, Cheruthoni Ar, Muthirapuzha, Perinjankutty Ar and Idamalayar, and most of the upstream tributaries flow through deep gorges and steep valleys. The general drainage pattern of the basin is dendritic in nature. The mainstream of the river bifurcates at Alwaye, and both the branches debouch into the Arabian Sea through two different estuaries. The north-trending branch joins the Chalakudy river and joins the Arabian Sea at Munambam through the Kodungallur–Azhikode estuary, whereas the south-trending branch forms numerous rivulets and joins the Vembanad–Kol wetland system and later joins the Arabian Sea through Cochin estuary.

Geologically, PRB has three distinct formations, such as crystalline rocks of Precambrian age, the Tertiary formations and the Quaternary deposits. The Precambrian

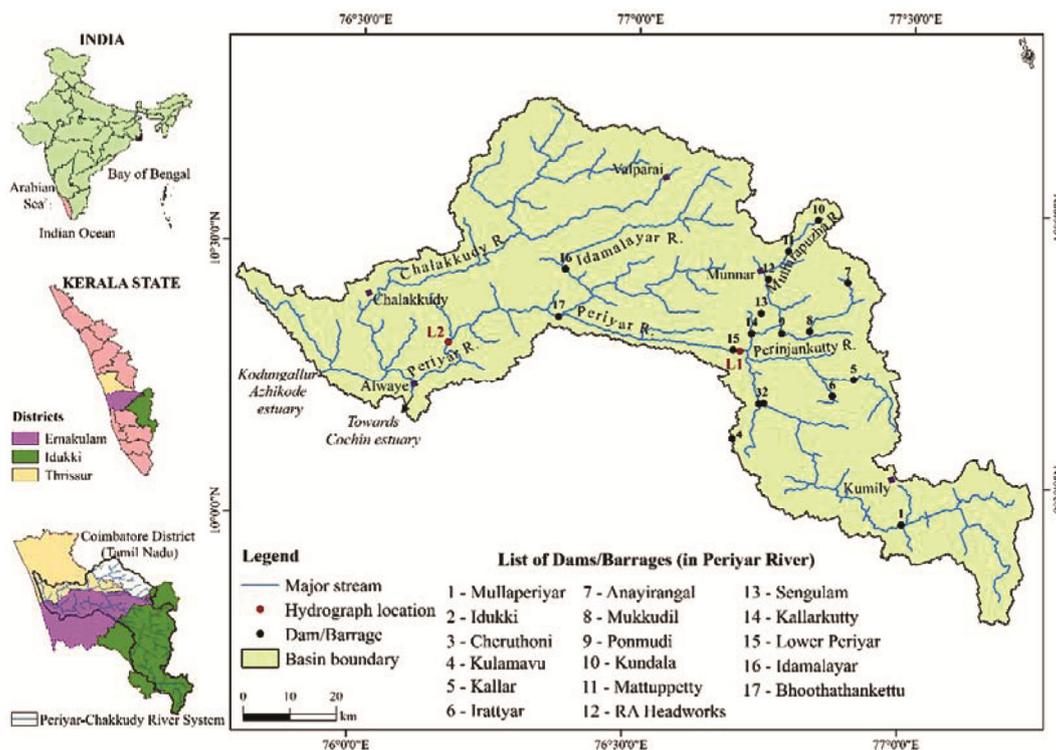


Figure 1. Periyar River Basin (including Chalakkudy River System), Kerala, India.

crystalline rocks are composed of the charnockite and migmatite groups (e.g. charnockites, charnockite gneiss, hypersthene-diopside gneiss, hornblende gneiss, and hornblende-biotite and quartz-mica gneiss/biotite gneiss), which are intruded by various felsic and mafic intrusives of age varying from Proterozoic to Tertiary. The sedimentary formations ranging in age from Eocene to Miocene (Vaikom, Quilon and Warkali beds) as well as Sub-Recent (laterite) to Recent (alluvium) overlie the crystallines along the coastal tract^{10,11}. The river basin enjoys a tropical humid climate, with marked wet and dry seasons. The upstream parts of the basin (in Idukki district) receives a mean annual rainfall of about 3677 mm, whereas the downstream parts (in Ernakulam district) experiences a mean annual rainfall of 3360 mm. The annual rainfall of the upper parts of the basin reaches more than 5000 mm, whereas the annual rainfall of the downstream parts ranges from 3233 to 3456 mm. The mean monthly maximum temperature of the upstream portion ranges from 25°C to 32°C and minimum temperature from 14°C to 19°C, while the mean monthly maximum temperature of the downstream part varies from 28°C to 32°C and the minimum ranges from 23°C to 26°C (refs 12, 13).

Based on the observed data of CWC (Integrated Hydrological Data Book 2012), the mean annual runoff of Periyar river measured at Neeleswaram (L2 in Figure 1) was 6686 MCM. The measured daily discharge by CWC at L2 from 1971 to 2017 is shown in Figure 2, where the effect of ISMR is evident as the periodic high-magnitude discharges every year. It is also noticed that

the duration of the lean flow period has considerably increased from 2010 onwards, compared to the previous years. The maximum daily discharge (6324 m³/s) during 1971–2017 was measured on 5 August 2013, and 80% of the high-magnitude daily discharges (>2000 m³/s) occurred either during the last week of July or during the first and second week of August.

The stream flow in PRB is heavily regulated by 17 dams and reservoirs (Table 1) and 2 barrages, which are constructed mainly for hydroelectric power generation as well as irrigation. The geographic location of these dams and barrages is depicted in Figure 1. The water level in the Idukki reservoir, the largest reservoir of the basin, is maintained by three dams, viz. Idukki, Cheruthoni and Kulamavu dams. Among the various dams, the largest dams are the Idukki–Cheruthoni–Kulamavu trio and the Idamalayar. The major irrigation projects in the basin are the Periyar Valley Irrigation Project, and the Idamalayar Irrigation Project. The major inter-basin transfer projects from PRB are the Mullaperiyar Dam (to Vaigai River, Tamil Nadu) and the Idukki Hydroelectric Project (to Muvattupuzha River, Kerala), and minor water transfer to Bharathapuzha river (Kerala) also co-exist in the basin.

Hydrological modelling

The hydrological simulation modelling of PRB was performed using HEC-HMS, which is a semi-distributed

hydrologic model with the ability to perform continuous as well as event simulation in dendritic watershed systems. HEC-HMS is an advanced version of the HEC-1 model which was developed in 1968 by the US Army Corps of Engineers. Since then, HEC-HMS has been widely applied in hydrology to model the rainfall-runoff process¹⁴, flood forecasting system planning¹⁵, assessing impact of land-use changes¹⁶ and runoff simulations in ungauged basins¹⁷. In HEC-HMS, the catchment is constructed by disintegrating the components of a hydrological cycle into manageable pieces, viz. precipitation, initial abstraction, evapotranspiration, infiltration, surface runoff and base flow. In this model, the physical description of the watershed is described using elements, viz. sub-basin, reach, junction, reservoir, diversion, source and sink. Computation proceeds from upstream to downstream direction and calculation of runoff are carried out in a sequential manner starting from canopy storage through surface or depression storage, infiltration and transform into base flow/surface flow hydrograph. Rainfall is the major input to this model along with other spatially distributed watershed characteristics, such as land use/land cover and soil, and the output from the model is the flow hydrograph.

Data used: The data used for setting up the HEC-HMS model for PRB were DEM, land use, soil and rainfall, and the details are given in the following sections.

The SRTM DEM (1 arc second; Figure 3 a) was downloaded (www.earthexplorer.usgs.gov) and processed to generate the stream network and basin boundary of PRB. The voids present in the data were filled and the sinks were removed to create a seamless hydrologically

corrected DEM. The basin was subdivided into 144 sub-basins based on the topography and location of major reservoirs. The river basin covers diverse physiographic types, ranging from the highlands in the upstream, the lowlands and coastal plains in the downstream and the midlands in-between. Maximum elevation of the basin is 2690 m above msl (at Anai Mudi), which is the highest peak south of the Himalayas, and roughly 85% of the basin area belongs to the highlands physiography.

The land use/land cover types of PRB (Figure 3 b) derived from IRS AWiFS data for the year 2010 with a

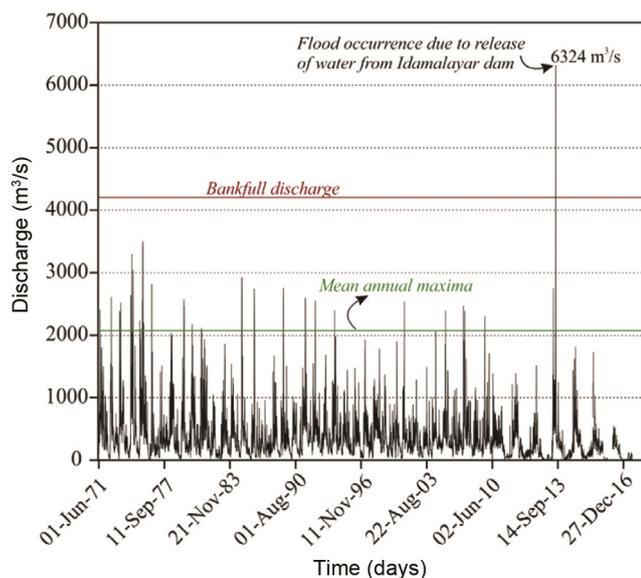


Figure 2. Daily discharge measured at Neeleswaram (L2 in Figure 1) by CWC (1971–2017).

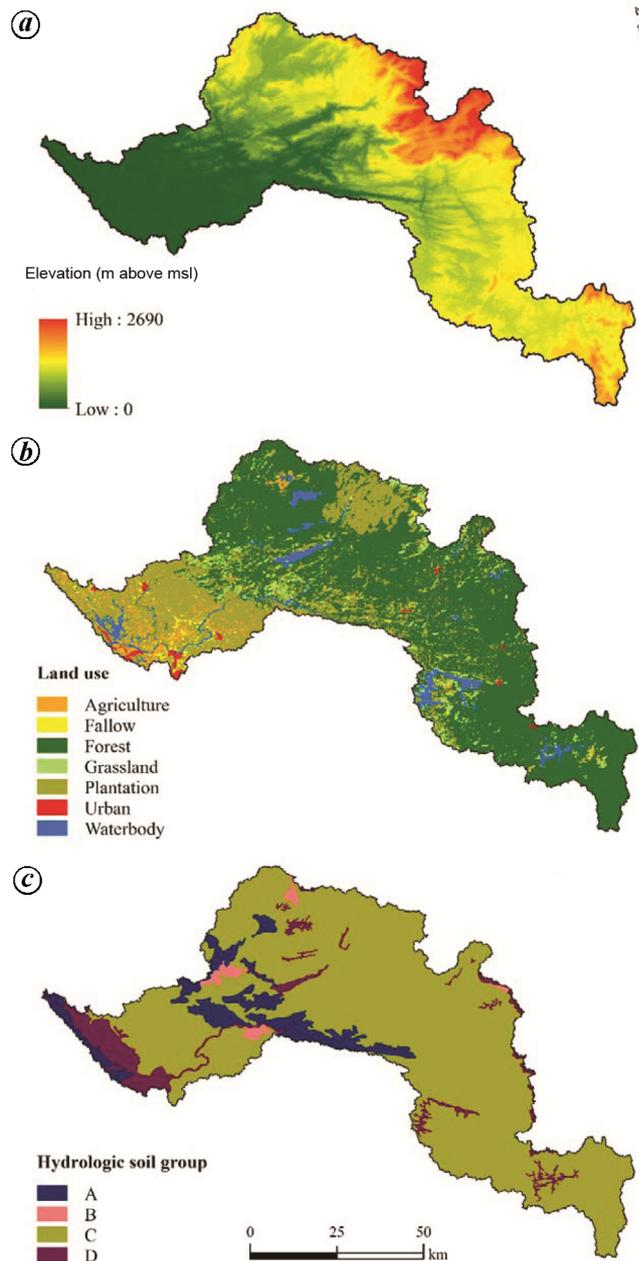


Figure 3. (a) DEM, (b) land use/land cover and (c) hydrologic soil group of PRB.

Table 1. Selected dams in the Periyar River Basin

Dam	Type	Year of completion	Length (m)	Maximum height above foundation (m)
Mullaperiyar	G&M	1895	365.80	50.29
Idukki	G&M	1974	366.00	169.00
Cheruthoni	E/G&M	1976	651.00	138.38
Kulamavu	G&M	1977	385.00	100.00
Kallar	E/G&M	–	67.91	12.19
Irattayar	G&M	1989	146.30	19.81
Anayirangal	E	1965	291.69	34.13
Ponmudi	E/G&M	1963	294.00	59.00
Kundala	E/G&M	1947	259.00	46.94
Mattupetty	E/G&M	1957	237.74	85.34
Sengulam	E/G&M	1957	144.50	26.82
Kallarkutty	E/G&M	1962	182.88	43.00
Lower Periyar	E/G&M	1996	284.00	41.00
Idamalayar	E/G&M	1985	373.00	102.00

E, Earthen; G, Gravity; M, Masonry. Source: WRIS-India.

spatial resolution of 60 m was obtained from the National Remote Sensing Centre (NRSC), Hyderabad. Major part of the basin is covered by forest, which is spread across the upstream and the central parts of the basin. The upstream parts are also covered by commercial plantations, such as tea, coffee, cardamom, whereas the coconut plantations and mixed crops (including spices, banana and tuber crops) dominate the remaining parts of the basin. Rubber is cultivated across the basin, irrespective of the physiographic domains, except in the high-altitude regions (>1500 m above msl). Paddy cultivation is concentrated in the downstream parts of PRB and practiced along the flat regions of the valley and floodplains.

In general, four types of soil are seen in PRB, viz. forest soil, hill soil, laterite soil and alluvial soil. The upstream areas of the basin are dominantly covered by forest and hill soils. The forest soils are developed from crystalline rocks under forest cover, and depth of the soil column shows significant spatial variability depending on the degree of erosion and vegetative density. In general, the soils are characterized by sandy clay loam to clay textures. The hill soils are mainly distributed along the slopes of the denudation hills, with textures varying from loam to clay loam. The extent of forest and hill soils are limited to upstream and central parts of the basin, while laterite soils, interspersed with alluvial soils are dominated in the midlands and parts of downstream areas of the basin. The percentage of gravel content in the laterite soil is relatively high. Alluvial soils are developed from marine, lacustrine and riverine sediments or its combinations. The downstream portion of PRB is mostly covered by alluvial soils. The soil data used in HEC-HMS were collected from the National Bureau of Soil Survey and Land Use Planning¹⁸. Based on the hydrologic soil group, most of the soils of the basin belong to class C, followed by class A (Figure 3c). The poorly drained soils (Class D) are

mainly distributed in the downstream parts, which have significant role in flooding.

Apart from the physical/topographical characteristics, spatio-temporal distribution of rainfall is also critical in quantifying the hydrologic response of the basin. However, due to lack of availability of time series of observed precipitation from the spatially-distributed rain gauges across the basin, the hydrological simulations of the current study were driven by satellite-derived precipitation data. The study employed half hourly cumulative gridded precipitation datasets of Integrated Multi-satellite Retrievals for GPM (IMERG) from 1 June to 31 August 2018 available at a spatial resolution of $0.1^\circ \times 0.1^\circ$ (www.pmm.nasa.gov/data-access/downloads/gpm). The IMERG data was bias-corrected using the simple ratio method with respect to the IMD rainfall from few selected rain gauges that were available to preserve the rainfall amount and spatial variability of the rainfall across the basin.

The distribution of the cumulative monthly rainfall of the basin shows considerable variability across space and time (Figure 4). Across PRB, the monthly rainfall during June varies between 50 and 1134 mm, whereas the monthly rainfall during July (118 and 1596 mm) and August (181 and 1686 mm) is relatively high. The maximum rainfall in August 2018 (Figure 4c) occurred in the catchments of Idamalayar and Muthirapuzha basins.

HEC-HMS model setup: In this study, the basin files were prepared for PRB, using HEC-GeoHMS, which is the pre-processor unit of the HEC-HMS. The topographic information in terms of DEM and stream network was employed to delineate the sub-basins, along with attributes for each sub-basin in terms of area, slope, flow paths, centroid of the sub-basins, etc. Infiltration or loss

from the rainfall was accounted using SCS curve number method (eq. (1))

$$P_e = \frac{(P - I_a)^2}{P - I_a + S}, \quad (1)$$

where P and P_e are the accumulated and effective rainfall (in mm) respectively, at time step t , I_a the initial abstraction considered which is calculated using the relationship ($I_a = 0.2S$) and S is the potential maximum retention, i.e. the maximum amount of water which can be stored in the soil. S is determined using the equation

$$S = \frac{25,400}{CN} - 254, \quad (2)$$

where S is in mm and CN is the curve number, which is determined based on the land use/land cover and soil type of the area.

PRB was subdivided into 144 sub-basins, and a weighted value of CN for each of the sub-basin was assigned by considering the variability of land use and soil classes in the area. After estimating runoff volume using SCS curve number method, the transformation of runoff volume into hydrograph was done using SCS unit hydrograph method (SCS UH), which is an event based dimensionless hydrograph in which the discharge is expressed as a ratio of discharge (q) to peak discharge (q_p) (i.e. q/q_p) and time as a ratio of time (t) to time to peak (T_p) of the unit hydrograph (i.e. t/T_p). For a given basin, the unit hydrograph is estimated using the peak discharge and lag time for the excess rainfall duration.

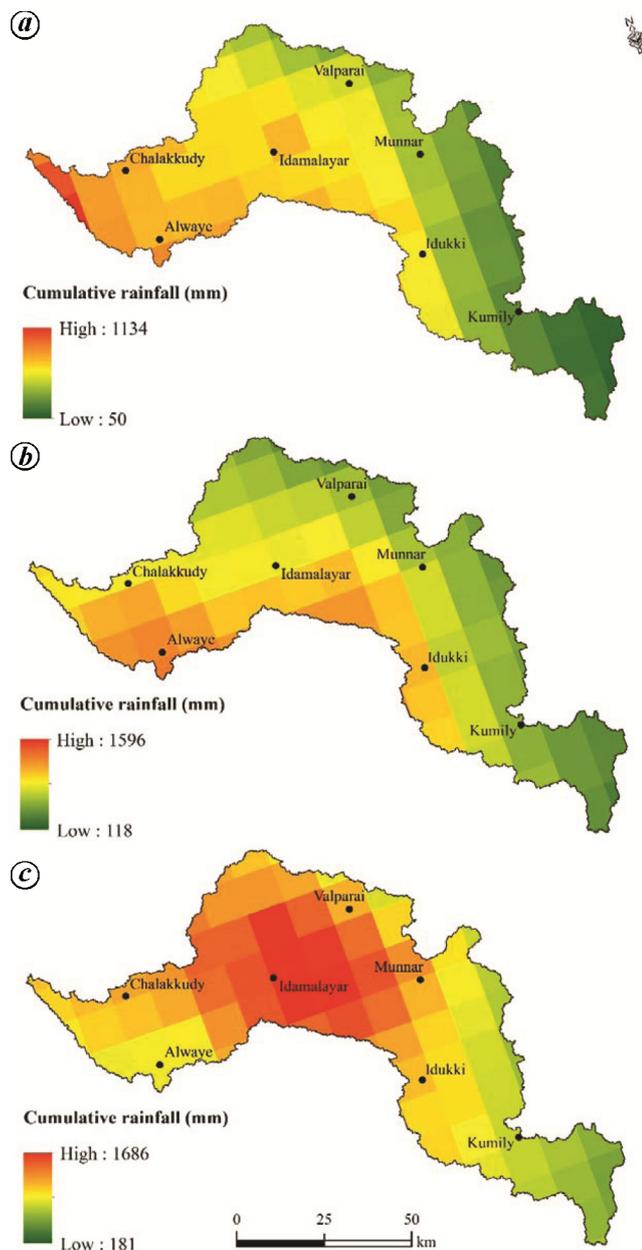


Figure 4. IMERG-based cumulative monthly rainfall in (a) June, (b) July and (c) August 2018 of PRB.

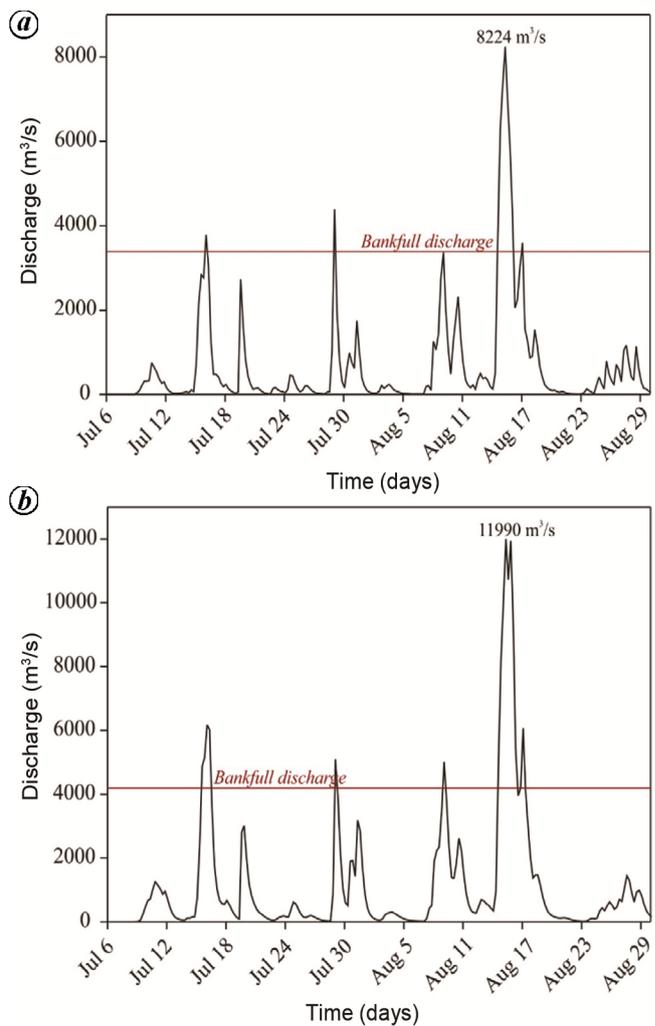


Figure 5. Hydrographs modelled by virgin simulation of the basin for (a) L1 and (b) L2.

Table 2. Description of the different scenarios used to model the hydrologic response of PRB

No.	Scenario	AMC	Remarks
Run 1	Virgin simulation for the 2018 event	AMC-III	Simulates the hydrologic response of the basin in the absence of the reservoirs to assess the impact of reservoirs on the flow hydrograph
Run 2	Event 2018 (reservoirs are at 85% storage capacity by end of July)	AMC-III	Simulates the actual event, where soil corresponds to wet antecedent moisture conditions due to relentless downpours. Reservoirs are close to FRL by the end of July. Hence, forced to release water into already flooded regions.
Run 3	Reservoirs are at 75% storage capacity by end of July	AMC-III	Simulation corresponds to wet antecedent moisture conditions. Leaves no option to contain the incoming flood waters during the month of August, thereby resulting in outflow/releases equal to reservoir inflow
Run 4	Reservoirs are at 50% storage capacity by end of July	AMC-III	Simulates with respect to wet antecedent moisture conditions. This allows to accommodate the flood storage, which is helpful in attenuating the peak flows.
Run 5	Reservoirs are at 25% storage capacity by end of July	AMC-III	Simulates considering wet antecedent moisture conditions. This has a provision to accommodate the flood storage, which is helpful in attenuating the peak flows.
Run 6	Reservoirs are at 75% storage capacity by end of July	AMC-II	Simulates with respect to average antecedent moisture conditions. Leaves no option to contain the incoming flood waters during August, thereby resulting in outflow/releases equal to reservoir inflow.
Run 7	Reservoirs are at 50% storage capacity by end of July	AMC-II	Simulation corresponds to average antecedent moisture conditions. It has the provision to accommodate the flood storage, which is helpful in attenuating the peak flows.
Run 8	Reservoirs are at 25% storage capacity by end of July	AMC-II	Simulates considering average antecedent moisture conditions. There is a provision to accommodate the flood storage, which is helpful in attenuating the peak flows.
Run 9	Reservoirs are at 85% storage capacity by end of June	AMC-II	Simulation corresponds to average antecedent moisture conditions. Leaves no option to contain the incoming flood waters during July and August. Hence release from the reservoir are active and consistent with the inflows received during July and August.
Run 10	Reservoirs are at 75% storage capacity by end of June	AMC-II	Simulates considering average antecedent moisture conditions. Leaves no option to contain the incoming flood waters during July and August. Hence release from the reservoir are active and consistent with the inflows received during July and August.
Run 11	Reservoirs are at 50% storage capacity by end of June	AMC-II	Simulates with respect to average antecedent moisture conditions. Initial storage conditions will serve as flood cushion for the inflows during July and August.
Run 12	Reservoirs are at 25% storage capacity by end of June	AMC-II	Simulation corresponds to average antecedent moisture conditions. Reservoirs are relatively empty before the onset of EREs in July and August. Provision to store the flood water received during July followed by active release in August.

From the assumption that the area under the unit hydrograph should be equal to 1 cm direct runoff, it is shown that

$$q_p = \frac{CA}{T_p}, \tag{3}$$

where $C = 2.08$ and A the drainage area in km^2 and q_p is expressed in $\text{m}^3/\text{s cm}$. T_p (in hours) can be expressed as

$$T_p = \frac{t_r}{2} + t_p, \tag{4}$$

where t_r is the duration of effective rainfall (in hours) and t_p is the lag time (in hours), which is approximated to $0.6 T_C$ (T_C is time of concentration of watershed).

The methods selected for modelling the components of runoff process are SCS curve number (loss method), SCS unit hydrograph (transform method) and kinematic wave method (routing option). These methods are selected based on the availability of data, suitability for the hydrologic condition, and the number of parameters (minimum) involved in modelling the process. For routing by kinematic wave method, information pertaining to river cross

sections such as shape of the cross section, width of the channel, length of the reach, etc. needs to be collected. In this study, the river cross section information was extracted from SRTM DEM (1 arc sec) and was later verified using Google Earth by overlaying the information extracted from the DEM. In addition, the extracted cross section information at Neeleswaram (discharge gauging site maintained by CWC) has been verified with measured cross section, and is found to match closely. Manning's roughness (n), which is a parameter required for kinematic wave routing was arrived at by field observation of the stream characteristics at various locations.

The model parameters such as curve number (CN) and lag time (t_p) were extracted from land-use and soil map, along with the hydrologic soil groups and soil characteristic information. Based on the land-use data and the soil information, the lumped CN value and t_p for each sub-basin were generated by HEC-GeoHMS. The default parameters thus derived were further fine-tuned so as to match the simulated hydrograph closely with the observed hydrograph reported at the CWC gauging site (Neeleswaram). The parameters for each of the methods in the HEC-HMS were kept constant throughout the analysis of different scenarios.

Scenarios: The flooding in PRB was simulated using different combinations of reservoir storages and antecedent soil moisture conditions (AMC) to assess hydrologic response of the basin to varying boundary conditions. As part of the study, twelve scenarios were simulated, which are given in Table 2.

Two control locations (L1 and L2 in Figure 1) were selected to generate the flood hydrograph for analysis. L1 is downstream of the confluence between the Periyar and Muthirapuzha rivers, and L2 is a downstream location in the PRB, where the gauge site (Neeleswaram) is maintained by CWC.

Results and discussion

Virgin simulation run for the 2018 event (run 1)

To understand the effect of regulation of stream flow in PRB by dams and barrages, a scenario was modelled in HEC-HMS without considering the dams and reservoirs (i.e. virgin simulation), and the entire basin was treated as unregulated. The simulated hydrographs with the EREs of 2018 for the virgin run shows peak discharges of 8,224 m³/s and 11,990 m³/s at L1 (Figure 5a) and L2 (Figure 5b) respectively.

Simulation of the flood events of August 2018 (run 2)

The catchment area of Periyar river witnessed relentless rains beginning from June 2018, resulting in the reservoir

storage to FRL by end of July⁴. The continuous spell of rainfall from July 6 has already made the soil of the basin saturated, and the EREs that occurred in August resulted in higher runoff than under-average conditions. This wet antecedent condition was simulated by assuming AMC-III condition as per the SCS curve number method with appropriate CN values. Idukki and Idamalayar reservoirs of the PRB have live storage capacities greater than 1000 MCM (i.e. 1460 MCM and 1018 MCM respectively). Since the reservoirs were near FRL by the end of July, the selected simulation time period was from 1 August 2018 to 31 August 2018 to represent the actual conditions prevalent within the basin.

The time step, which was less than the time of concentration (T_C) of individual sub-basins was adopted to ensure that peak flows were effectively captured by the model. The HEC-HMS run was performed with curve number corresponding to AMC-III and reservoir storage levels at 85% at the beginning of model run on 1 August 2018. The hydrograph locations, where the flow hydrographs were extracted from the HEC-DSS database of the model run are: (a) inflows to Idukki reservoir, (b) location 1 (L1), which captures the releases from Idukki reservoir along with the hydrologic response of the upstream catchments within Idukki district, and (c) location 2 (L2) at Neeleswaram (where a CWC stream gauge site is located), which captures releases from Idukki and Idamalayar reservoirs along with the free catchment response. Figure 6a–c shows the flow hydrographs simulated at the control points for the time period 1–31 August 2018. Since the observed hydrograph except at L1⁴ is at six hourly intervals, the simulated flows were also generated at intervals of 6 h to compare the model simulated and the observed flow hydrographs (Figure 6a and c).

The HEC-HMS simulated the peak inflow of 2763 m³/s to Idukki reservoir on 15 August 2018 at 20:00 h, and the maximum release of 1860 m³/s on 15 August 20:00 h (Figure 6a). The measured peak inflow to the reservoir and the release were 2532 m³/s and 1614 m³/s (15 August 22:00 h) respectively. A comparison of the measured and modelled peak discharges exhibited less than 10% deviation, which indicates that the model captured the flood event reasonably well in terms of the peak discharge and releases from the reservoirs.

Figure 6b is the simulated flow hydrograph at L1, where magnitude of the peak flow reached up to 5523 m³/s. Since L1 does not have observed records, the simulated hydrograph was not compared to assess the accuracy of the representation of the hydrograph. Figure 6c shows the flow hydrograph (simulated versus observed) at L2, which geographically corresponds to the CWC gauging site in the downstream of Periyar river. HEC-HMS generated a maximum discharge of 9965 m³/s, while the observed peak discharge was 8800 m³/s. A quantitative comparison between the modelled and the

observed hydrographs for 14–18 August evidently suggests realistic agreement. The difference in the magnitude of the peak discharges (i.e. 12% over-prediction by the model) can be attributed to the differences in the rainfall occurred and IMERG precipitation data and the model parameter uncertainty to a certain extent. In addition, the possible anomalies in the river cross section information that is extracted from the DEM could also lead to some level of inaccuracy in the simulated flow, though found

to be very minimal during a sensitivity analysis. The numerous landslides which occurred in PRB during the EREs⁶ could have altered the hydrologic response of the catchment, which may also be a reason for the differences in the peak flow estimates. Compared to virgin simulations, which resulted in peak flow magnitudes 8,224 and 11,990 m³/s at L1 and L2 respectively (Figure 5 a and b), it can be observed that the reservoirs were effective in reducing the peak flows to the scale of 2500 m³/s.

It is noted that the peak discharge at L2 was 9965 m³/s (Figure 6 c), while the maximum release from the Idukki reservoir was only 1860 m³/s (Figure 6 a). Therefore a major share of the peak flow at L2 is contributed by the catchment area of the major tributaries, such as Perinjankutty, Muthirapuzha and Idamalayar. In order to assess the contributions from the different tributaries, the flow hydrographs generated along the four major branches of the Periyar river were plotted along with the hydrograph generated at L2 (Figure 7). The relative magnitude of individual hydrographs that can be inferred from Figure 7 points to the observation that EREs, coupled with saturated soil moisture conditions and physical characteristics of the catchment, had significant contribution in the flow hydrograph simulated at L2. A quantitative comparison indicates that the hydrologic response of the major tributaries of the Periyar river was also significant in terms of magnitude of flows, compared to the reservoir releases. For example, the flood discharges from the tributaries such as Perinjankutty (3500 m³/s), Idamalayar (2828 m³/s) and Muthirapuzha (2037 m³/s) were comparably higher than the release from Idukki reservoir (1860 m³/s). This indicates that the role of releases from Idukki reservoir in causing the flood havoc was less, as Perinjankutty river, which is nearly uncontrolled,

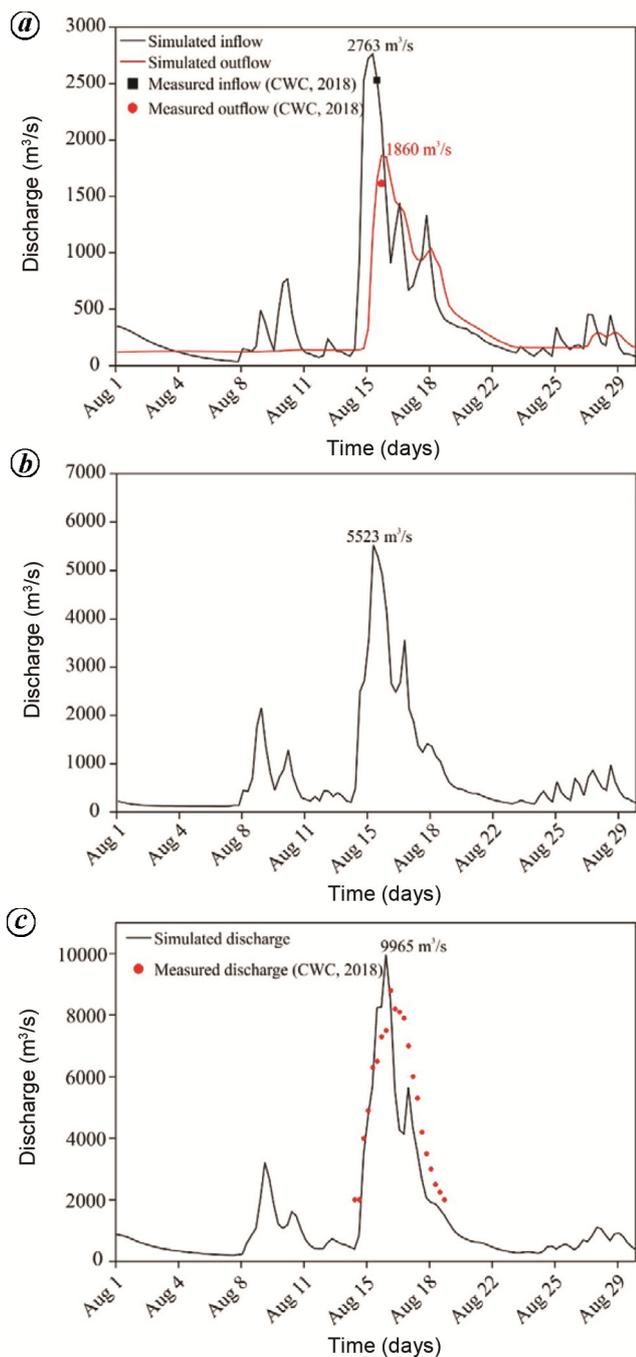


Figure 6. Simulated hydrographs at (a) Idukki reservoir, (b) location 1 (L1) and (c) location 2 (L2). Simulated flows were compared at Idukki reservoir and L2 with measured flows⁴.

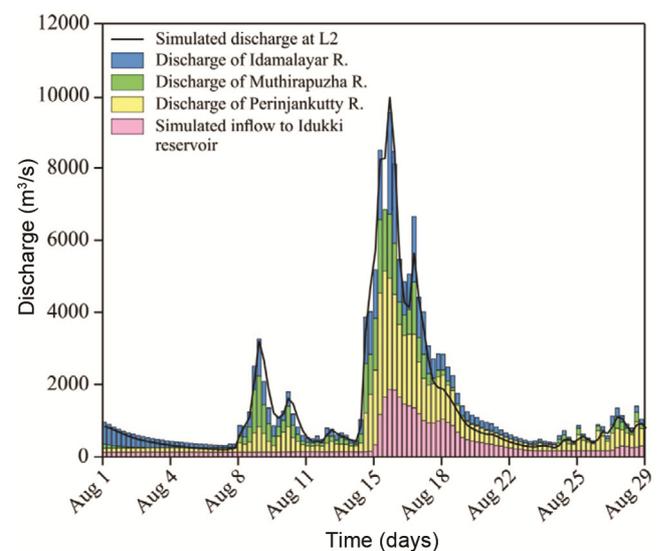


Figure 7. Comparison of simulated flow hydrographs along the major tributaries of the Periyar river and L2.

contributes almost twice the amount of release from Idukki reservoir.

Comparison of different scenarios (runs 3 to 12)

The flood that occurred in PRB was simulated with respect to varying scenarios of reservoir storage capacities at different timelines and different soil moisture condi-

tions. Figures 8 and 9 show the flow hydrographs corresponding to varying storage capacities (i.e. 75%, 50% and 25%) at the end of July 2018 under AMC-II (average) and AMC-III (wet) conditions at L1 and L2 respectively. It is noted that the antecedent soil moisture condition does not have significant influence on the simulated peak flow as the difference in magnitude between both the cases (Figures 8 and 9) is found to be within 10%.

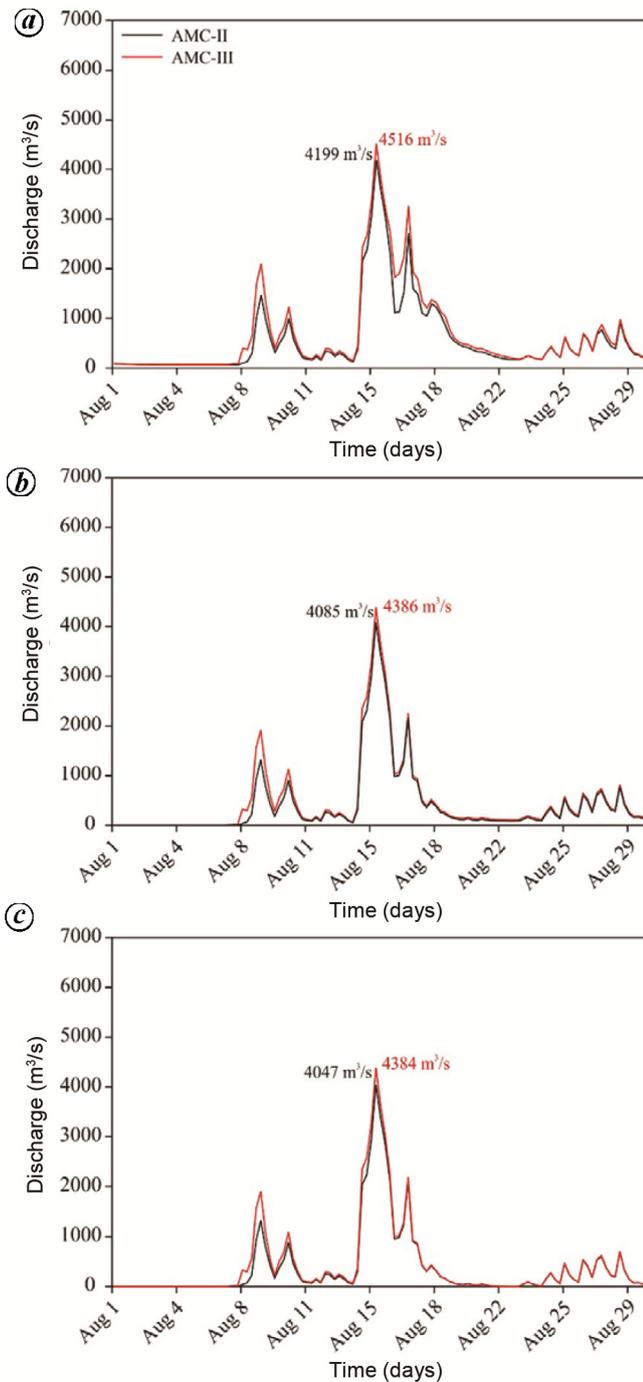


Figure 8. Flood hydrographs at L1 when reservoirs are at storage capacities (a) 75%, (b) 50% and (c) 25% by the end of July 2018 with AMC-II and AMC-III conditions.

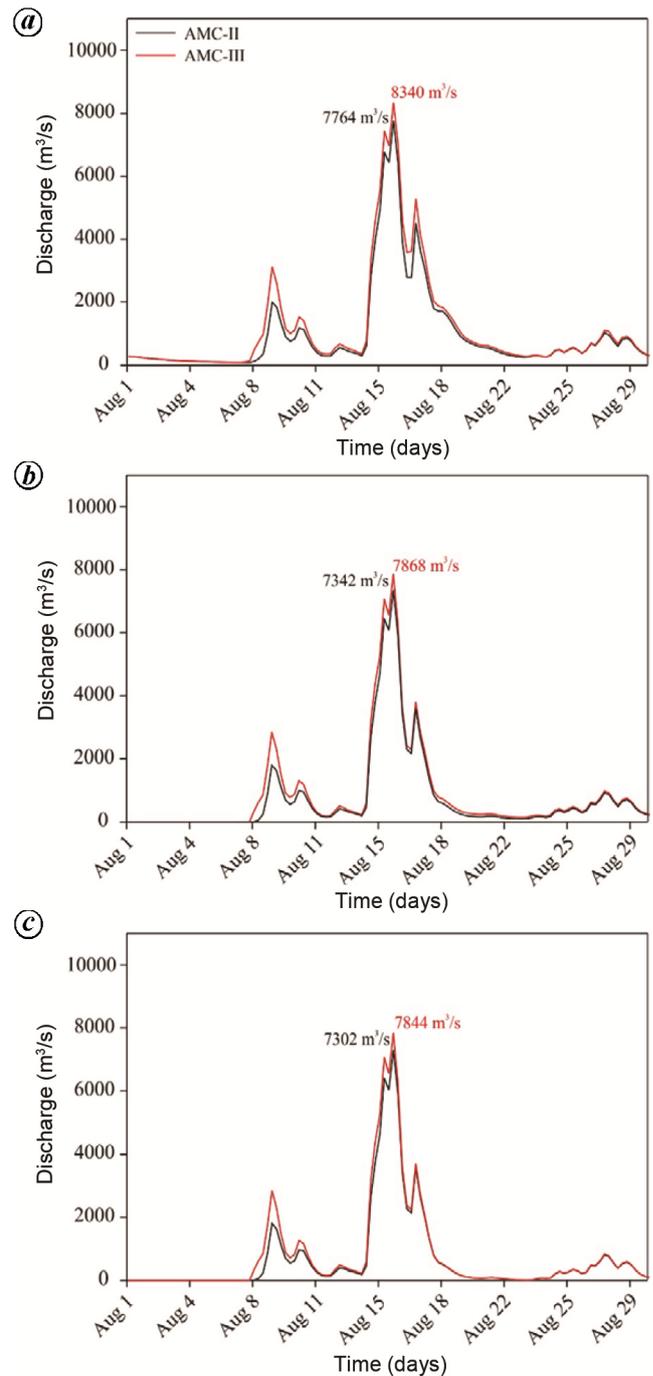


Figure 9. Flood hydrographs at L2 when reservoirs are at storage capacities (a) 75%, (b) 50% and (c) 25% by the end of July 2018 with AMC-II and AMC-III conditions.

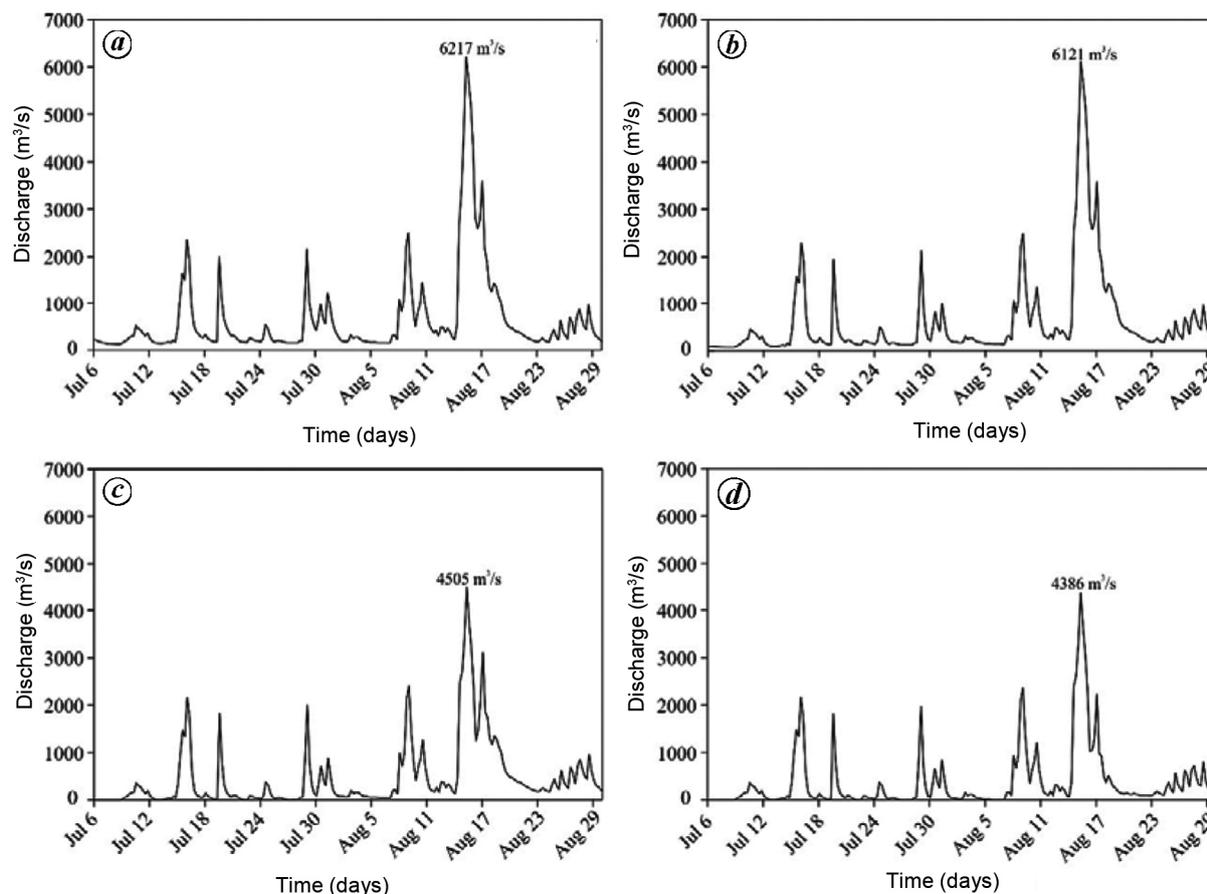


Figure 10. Flood hydrographs at L1 when reservoirs are at storage capacities (a) 85%, (b) 75%, (c) 50% and (d) 25% by the end of June 2018 with AMC-II conditions.

The simulation run corresponding to storage level at 75% resulted in a peak discharge of $4516 \text{ m}^3/\text{s}$ and $8340 \text{ m}^3/\text{s}$ (Figure 8 a and 9 a) at L1 and L2 respectively, compared to a peak discharge of $5523 \text{ m}^3/\text{s}$ and $9965 \text{ m}^3/\text{s}$ (respectively for L1 and L2) for 85% storage level (Figure 6 b and c). The reduction in storage capacity of reservoirs, from 85% to 75% through early release, helps reduce the peak flow at L1 by 18% and at L2 by 16%. Similarly, the reduction in reservoir storage from 85% to 50% or 25% reduced peak discharge by 21% at both locations. The bank full discharge at L1 and L2 approximately being $3400 \text{ m}^3/\text{s}$ and $4200 \text{ m}^3/\text{s}$, it is apparent that the reservoir operation could not have helped in avoiding the flood situation. Further, the simulations with reservoirs at 50% and 25% of their gross storage capacities hardly showed any significant difference in the generated flows at both L1 (Figure 8 b and c) and L2 (Figure 9 b and c). Hence, the reported flows at downstream locations will be insensitive to the storage status of the reservoirs, if the reservoir is filled to less than 50% of its capacity.

On the other hand, the simulations clearly indicate that flood peaks could have been attenuated by an early release of reservoir storage (flood cushion up to 25%)

prior to the occurrence of the EREs, though to a maximum level of only 21%. However, as the reservoirs are designed and currently operated for hydroelectric power generation, a policy that directs emptying the reservoir has critical limitations. The current reservoir operation policy is based on water conservation so as to maintain the reservoir levels close to FRL throughout the monsoon season to ensure maximum power generation. Therefore, it is suggested that one should revisit the operation rule curves of the reservoirs and derive fresh rule curves in order to operate the reservoirs not only as power reservoirs but also as flood control reservoirs. The goal of these rule curves should include minimization of flood damage besides maximization of benefit due to power generation.

In order to assess the effect of maintaining the reservoirs at 85%, 75%, 50% and 25% storage capacities at the end of June 2018, corresponding flow hydrographs were generated at L1 and L2 (Figures 10 and 11). Since June is the beginning month of ISMR, the antecedent moisture status was assumed to be of average conditions (i.e. AMC-II). It is noted that flood peak at L1 and L2 remained similar in this scenario (85% storage at the end of June 2018) compared to run 2 (85% storage at the end

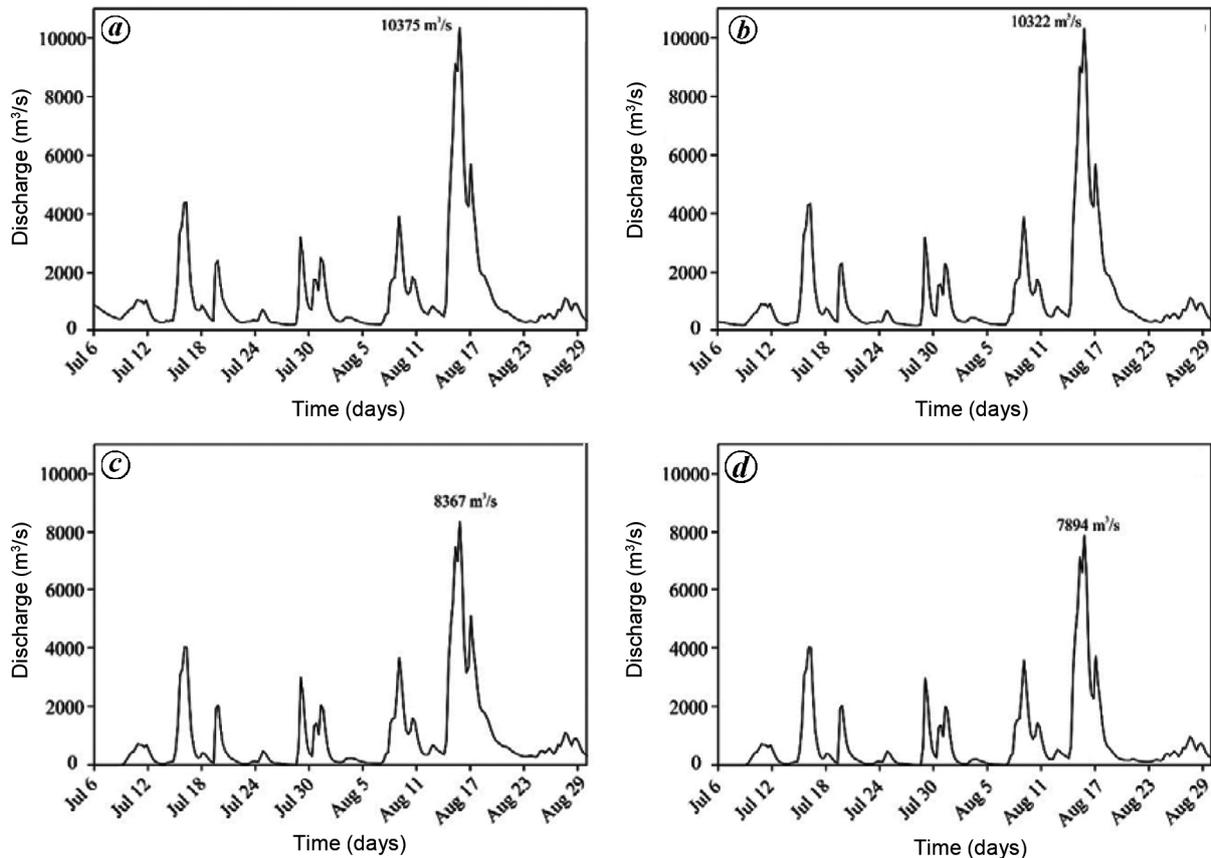


Figure 11. Flood hydrographs at L2 when reservoirs are at storage capacities (a) 85%, (b) 75%, (c) 50% and (d) 25% by the end of June 2018 with AMC-II conditions.

of July 2018). This is because of the continuous spell of rainfall (though not heavy) during the month of July 2018, which resulted in minimal releases from the reservoir due to conservation operation. Consequently, the reservoirs attained near FRL storage by the end of July 2018. Hence, it would have been critical to maintain the flood cushion of 15% to 25% by the end of July rather than by the end of June.

Remarks

The role of dams in mitigating floods has been studied globally by various researchers/agencies. The California Flood Emergency Action Team report on the 1997 floods claimed that flood control dams in major river systems reduced deadly flood flows by half or more, saving lives and significantly reducing property damage (www.water.ca.gov). Considering the rivers of USA, the per cent of rivers with greater than 25% reduction in the median annual flood is 55% for large rivers, 25% for medium rivers and 10% for small rivers¹⁹. The analysis of 37 rivers in the United States to study the impact of dams in the annual peak flow of the rivers also showed a significant reduction in the average annual peak flow values

between 7.34% and 95.14% (ref. 20). A comparison of the hydrographs simulated for the virgin condition (run 1) and the actual event in 2018 (run 2) suggests a 33% attenuation of peak flow at L1 and 17% at L2. Note that there are 11 reservoirs upstream of L1, whereas there are only 3 reservoirs upstream of L2 up to L1. Therefore, a major attenuation of the flood occurred by the interconnected reservoirs upstream of L1, and resulted in higher attenuation level compared to the attenuation at L2. The results in general indicate the positive role of dams/reservoirs in flood mitigation in the PRB, as is expected. Earlier studies had also observed that 41% of the net runoff of Periyar river (at downstream reaches) is reduced due to the construction of dams²¹, while another study²² reported that the flood moderation and fair-weather flow augmentation due to dams resulted in hydrologic alterations in PRB. In this premise it is evident that the dams in PRB did serve the flood moderation with its envisaged flood cushion, though the system is designed for conservation operation.

Historical rainfall data of the Kerala state indicate that maximum rainfall is experienced in June and July months, compared to August and September. Rainfall analysis of the state⁹ indicates that roughly 70% of the

mean ISMR in Kerala (considering the period 1871–2012) occurs during June and July months, whereas the contribution during August month is less than 20%. Moreover, the rainfall experienced during August and September shows relatively larger temporal variability (i.e. coefficient of variation = 41% and 53% respectively), compared to the monthly rainfall in June and July (i.e. 28% and 32% respectively). A frequency analysis of the rainfall in the PRB during the months of June and July indicated that the rainfall magnitude received in June 2018 had a return period of only 3 years, and July 2018 had a recurrence interval of 8 years. However, the August 2018 rainfall was found to be of 145 years return period. Note that the frequency analysis was conducted for the average rainfall for PRB, using rainfall data of 55 meteorological stations in PRB with varying length of data record for 105 years (1901–2006). The study⁵ reported that the 1, 2, and 3-day extreme rainfall in Kerala during August 2018 had return periods of 75, 200 and 100 years respectively. The extreme rainfall during the first 15 days of August 2018 in the catchment area of Idukki and Mullaperiyar dams had a return period of more than 500 years⁵. Though it appears to be exorbitant it is plausibly owing to uncertainties in the gridded rainfall information used for the analysis. Despite the uncertainty, it is obvious that the rainfall in August 2018 was of a very high recurrence interval.

As mentioned earlier, none of the dams/reservoirs in PRB has been designed for flood control purpose, but for hydropower/irrigation, and therefore the operation policy has been to maintain the reservoir levels close to FRL throughout the monsoon season to ensure maximum power generation. The PRB has experienced only two severe flood events in recent history, one in 1924 and the other in 1961. In 2013, downstream areas of Bhoothathankettu barrage, including the Cochin International Airport Ltd. were inundated due to release of water from Idamalayar dam. The frequency analysis of the historic annual flood discharge data recorded at L2 (during 1971–2018) indicated that the flood event of August 2018 had a return period of 142 years. The results suggest that the probability of EREs and associated flood event of the kind experienced in August 2018 in PRB is very small, and therefore any planned operation could not have helped in mitigating floods of such magnitude as the reservoir design and/or operation might not have considered such events.

In addition, accuracy of the forecasts is also important in reservoir operations. Currently, decision-making in the water resources and disaster management sector in India depends on the quantitative precipitation forecasts (QPF) from IMD. Though the accuracy of district level medium range rainfall forecast (up to 5–7 days in advance) is 75–85% in monsoon season (www.pib.nic.in/newsite/PrintRelease.aspx?relid=108707), the accuracy of QPF with regards to rainfall magnitude is low. On the other hand,

accuracy of the medium range weather forecasts by IMD at higher lead times is greatly debated. The probability of detection (POD) of higher rainfall (>25 mm/day) at short range (3-day) or medium range (5-day) even with the ensemble of models is still low at about 20% to 30% only²³ with a large probability of false alarm²⁴. As the operation of reservoirs for hydro-power or irrigation purposes has a huge economic benefit associated with it, further improvement in the reliability of QPF, especially those of EREs with a lead time of 3 to 7 days is extremely important. Therefore, improvement in the reliability of forecasting of EREs coupled with a good inflow forecasting system could help improve the management of reservoirs.

On the other hand, the link of the ERE that caused the devastating flood during August 2018 with the global climate change is also a concern. Many researchers have attributed climate change to an increase in EREs across the globe^{25–27}. In the Indian context too, many researchers have observed significantly increasing trends in the frequency and the magnitude of EREs during ISMR^{28–30}. However, the underlying physics for the increased EREs over Indian region is still an enigma, as the researchers have proposed varied hypotheses^{29–31}. In addition, it is demonstrated that the occurrence of EREs during ISMR is mostly localized over the west coast, central parts of India and northeast India³⁰. Therefore, developing a reliable early warning system, specifically for EREs, is a challenging task.

The experience during the August 2018 flood in Kerala underscores the significance of reviewing the flood management strategies and flood mitigation measures. The study suggests revisiting the rule curves of the reservoirs by considering dams as multi-purpose and multi-reservoir water resource systems, and developing integrated reservoir operation policies. The goal of the modified rule curves should include minimization of flood damage

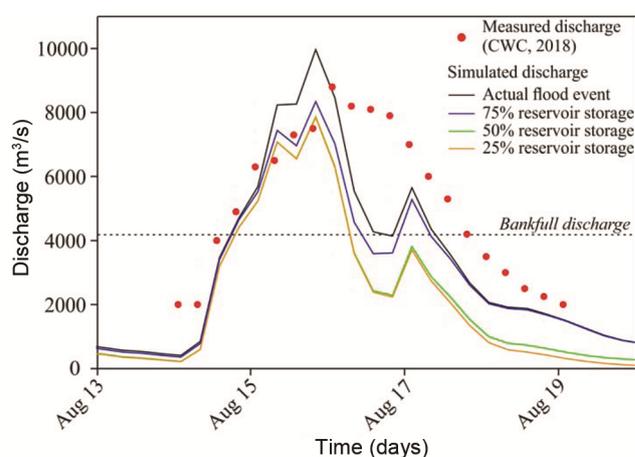


Figure 12. Comparison of the simulated peak discharge (part of the hydrographs during the flood peak) for different reservoir storages at Neeleswaram, along with the measured discharge during the flood event.

besides maximization of benefits due to power generation and irrigation. This aspect needs in-depth studies on improving weather forecasts, reservoir inflow forecasts and multi-reservoir/multi-objective operational rule sets. Studies on these aspects need to be initiated with highest priority to be better prepared to effectively manage such EREs in the future.

Summary and conclusion

The extensive flooding during August 2018 in Kerala (India) due to two consecutive EREs (during 8–10 and 14–19 August 2018) affected millions of people, and caused substantial damages to infrastructure as well as the physical environment. The extraordinary combination of the occurrence of the EREs, along with near FRL reservoir storages, made the situation challenging to manage, and coerced the authorities to open the gates of most of the dams in the state to release water. Hence, the role of dams and its operations in causing/mitigating the flood has been criticized and debated in the scientific, social and political contexts, and the discussions explicitly held the reservoir operations practiced during the flood and the lack of adequate warnings responsible for the paroxysm. One of the major river basins that was affected by the flood was PRB, which consists of 17 dams/barrages that are interconnected. An analysis of the rainfall record indicated that the rainfall received in PRB during August 2018 had a return period of 145 years. Similarly, the observed flood on record during August 2018 in PRB (Neeleswaram; location 2) had a recurrence interval of 142 years. In this premise, the question, whether an early release of the water stored in the PRB reservoirs could have helped or not in attenuating flood peaks, still remains unexplained. Hence, a modelling exercise to simulate the role of dams as well as reservoir operations in causing the flood of August 2018 was performed using HEC-HMS. The study analysed different scenarios with combinations of reservoir storages (85%, 75%, 50% and 25%) at different time periods (end of June and end of July), along with different AMCs (average and wet conditions).

The model simulated the flood discharge fairly well, showing insignificant temporal offsets. The simulated and observed peak flows to Idukki reservoir (upstream of PRB) were 2763 and 2532 m³/s respectively. Similarly, the maximum discharge simulated at Neeleswaram was 9965 m³/s against the measured value of 8800 m³/s. The flood hydrograph between PRB without dams (virgin simulation) and the actual flood event (simulation with reservoirs at storage capacity 85% by the end of July 2018) showed reduced peak discharge at location L1 by 33% (immediately downstream of Idduki), and at location L2 by 17% (at Neeleswaram), indicating the positive role of dams in attenuating the flood magnitude. The study also indicated that the major share of the total flood flow was by Perinjankutty (3500 m³/s), which is a near uncon-

trolled tributary, while the controlled releases from Idukki had contributed only 1860 m³/s. It is noted that Idamalar reservoir releases, along with the free catchment downstream of the reservoir contributed 2828 m³/s of the total flood, while Muthirapuzha basin contributed 2037 m³/s. The results indicated that the role of releases from the major reservoirs in the PRB to cause the flood havoc was less. It is also observed that the antecedent soil moisture condition had hardly any role in controlling the flood peak of the basin as the difference in the flood magnitude between AMC-II and AMC-III conditions was less than 10%. Note that the soil moisture condition in general reach AMC-III by the end of June in most years.

The results suggest that the peak flow at Neeleswaram could have been curtailed by early release of the reservoir storage and making the end of month storage less than 85% of the storage capacity. However, this strategy has critical limitations as these reservoirs are designed for hydropower generation, and current reservoir operation policy is based on water conservation so as to maintain the reservoir levels close to FRL throughout the monsoon season to ensure maximum power generation. However, emptying the reservoir to 75% of the total storage by the end of July suggested a reduction in peak at Neeleswaram, though only 16%. A controlled storage of 50% or 25% in all the reservoirs suggested a peak attenuation by 21% from 9965 m³/s. The simulated flood peak (part of the hydrograph during the flood peak) corresponding to different reservoir storages (85%, 75%, 50% and 25%) along with the observed hydrograph at Neeleswaram is presented in Figure 12 for a direct comparison. With the bank full discharge at Neeleswaram approximately being 4200 m³/s, it is apparent that the reservoir operation could not have helped in avoiding the flood situation. In addition, the reliability of the rainfall forecast at higher lead times was also a concern for the reservoir operation. Further, as the probability of EREs of this kind in the month of August in PRB is very small (0.6%), any planned operation could not have helped in mitigating floods of such magnitude as the reservoir design might not have considered such events.

The present analysis of the August 2018 flood in PRB, suggests revisiting the rule curves of the reservoirs by considering the dams as multi-purpose and multi-reservoir water resources systems, and developing integrated reservoir operation policies so as to maintain the balance between flood control and other system objectives, such as hydropower generation and irrigation. However, it may be noted that the success of flood management exclusively depends on the accuracy of prediction of EREs at higher lead times.

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