FLOOD MITIGATION BY DAMS IN KRISHNA BASIN OF MAHARASHTRA STATE

Abstract

The river Krishna originates in the western ghats of the State of Maharashtra in India. It flows through the Satara, Sangli and Kolhapur districts of Maharashtra, before meeting the Bay of Bengal. In 2019, widespread heavy rains occurred from 28th July to 12th August in the Krishna basin resulting in a flood situation. The flood situation started aggravating from 1st August and reached its worst on 8th, 9th and 10th August. Almost 2/3rd of the Sangli and Kolhapur districts were underwater for more than 10 days. The major flood-prone spots are Sangli, Kolhapur and Rajapur, which receive floods from free as well as dam intercepted catchments. There are 22 dams in the basin upstream of the above three spots on various tributaries. These dams have major storage below spillway crest and minor above it, against operatable gates. Dams across rivers, whether they create or absorb floods, has always been an issue of debate. This paper presents a study of the impact of flood releases from various reservoirs in the Krishna basin from 30th July to 17th August 2019, along with the role played by three major dams i.e., Koyana, Warna and Radhanagari. An ideal condition without dams is studied to assess the effect of reservoirs on downstream floods of the region.

The study reveals that during the above period, average flood values at Sangli and Rajapur have more contributions from free catchment areas, rather than dam spills. However, in critical flood situations from 6th to 9th August 2019 the major contribution in flood was from unavoidable dam spills. The flood absorption capacity of dams is classified into two stages. Stage I is till the water level reaches spillway crest level. Stage II is after the water level rises above spillway crest level and water is stored/released against gates. In Stage I, the upstream dams absorbed 3072 Mcum of water, mitigating the disaster in the flood-prone area. In Stage II, the peak discharge values were reduced for Koyna and Warna dams by 19% and 32% respectively. Also, the peaks were delayed by 2 days which contributed to flood mitigation. In the analysis of the condition (Without Upstream Dam Condition), the situation would have created an adverse impact on the flood-prone area.

Keywords: Flood Mitigation**,** Flood Inundation, Flood Absorption, Dam Releases, Intercepted Catchment.

Introduction

Natural disasters are serious threats that not only cause life-threatening events but also trigger the depletion in ecosystems and thereby causing socio-economic losses (SAMHSA 2017). Floods have been one of the major natural disasters from ancient times but in the wake of climate change, their duration and intensities have been increased significantly (Sholihah et al. 2020). For agricultural development and to preserve water as an essential commodity dams are constructed across the rivers from prehistoric times. (Baba 2018). These Dams significantly change hydrological processes in the natural river channel (Zhao et al. 2020). Because of controlled reservoir operation, a dam across a natural river changes flood characteristics downstream. These controlled reservoir operations may or may not help flood mitigation depending on basin and dam characteristics. The natural river carrying capacity is also an important factor for dam releases. These dam releases can be pre-flood, during flood and post-flood. There is always criticism on dam operating authorities regarding the failure of managing the flood through reservoir operations (Sudheer et al. 2019). The study of floodplain dynamics and flow regulation by reservoirs shows that the dams play important role in flood and the average number of people exposed to flooding below dams amount to 9.1 and 15.3 million per year globally (Boulange et al. 2021). The dams in Japan, the USA and Spain have played an important role in flood mitigation (Berga 2005). As per (Mei et al. 2017), dams are the key structures in mitigating floods and the ability of dams to regulate downstream flooding has received worldwide attention.

On the other hand, in some cases, the increase in flood levels downstream of the major dams is a concern (Yang et al. 2017). The study of Periyar River Basin, Kerala, India revealed that the reservoir operations will not always help in flood mitigation by emptying the reservoir in advance (Sudheer et al. 2019). The study of the flood disaster in Surat, India shows that Ukai dams releases created floods at Surat in July 2006. (Thakkar 2007). The dam releases can accumulate stagnant water or worsen the stagnant water which is already there by heavy rainfalls (Caroline Peter Diman and Wardah Tahir 2012).

The downstream flood mitigation can be achieved by the pre-release. The decision of pre-release from dams needs strong support from accurate weather forecast (Sudheer et al. 2019) The decision support system for dam releases developed for the Tone River basin, Japan is with main objective to minimize the flood volume at control points downstream and to maximize reservoir storage (Valeriano et al. 2010). But this may lead to forceful excessive releases in later stages of continuous rainfall in basins like Krishna.

An important balance between dam storage and pre-release has risks that one has to afford in crucial conditions (Hidayah Ishak and Mustafa Hashim 2018). Every dam has its impact on its downstream flood peak discharges and flood frequency curves. The degree of flood peak attenuation increases is proportional to storage capacity and spillway dimensions. It also depends on reservoir position along the channel (Volpi et al. 2018). Upstream dams reduced the magnitude of peak discharges in normal rivers and increased in dead rivers. (Mei et al. 2017). The flood contribution/absorption of the dams is dependent on height, storage, spillway discharge (Lempérière 2017). It is essential to operate upstream reservoirs with improved rule curves keeping the flood control aspect in consideration (Visweswararao and Viswanadh 2019). In flood hazard mapping downstream of reservoir detailed knowledge of reservoir operating rules is essential (Zhao et al. 2020).

The Krishna River having a length of about 1400 km is the fifth-biggest river in terms of water inflows and river basin area in India, after the Ganga, Godavari and Brahmaputra covering almost 8% of the total geographic extent of India (Kulkarni and Deshpande 2014). It originates in the Western Ghats, at an elevation of about 1337 m, at Mahabaleshwar covering an area of 21114 km^2 and 282 km in length in Maharashtra. The main tributaries of the Krishna River in Maharashtra are Koyna, Warna, Panchganga and Dudhganga.

In the year 2019, heavy rains occurred from 28th July to 12th August. The rains were continuous and widespread. Most intensive rainfall occurred from 1st August 2019 to 7th August 2019 at Sangli, Satara and Kolhapur districts having received 406%, 431%, and 344% of weekly average rainfall. The flood situation in Sangli and Kolhapur started aggravating from 1st August and reached its worst on 8th, 9th and 10th August. Almost 2/3 of the Sangli and Kolhapur districts were underwater for more than 10 days, including agricultural land with standing crops. There was heavy inundation in rural areas, with a water spread of 5 to 10 km beyond both banks of the River Krishna. All modes of transport and communication were disrupted.

Independently, media and social activists hypothesized their reasons for the flood. They concluded the early impoundment in Maharashtra dams (particularly Koyna) and the release of excessive water in critical periods created floods not only in Maharashtra but also in Karnataka. One writ petition was filed in the Supreme Court of India claiming for human and property losses due to mismanagement of reservoirs in the basin, against the Water Resources Department, Government of Maharashtra.

Existing research shows that the flood mitigation characteristics of the basin with dams may differ from case to case. In some cases, it may mitigate, while in others it may intensify the floods. Hence each case and basin needs study of the potential of downstream flood mitigation by dams separately. It is necessary to identify whether the dams will help in mitigation or intensify the floods in the area. The concept of pre-release may not be useful in all cases. The downstream flood frequency and peaks may differ for different cases and spillway releasing capacities, dam heights, dam locations, and basin characteristics etc. The Krishna Koyna and Yerala tributaries are having a greater tendency to peak discharge in a short period because of the high relief ratio, high ruggedness number and less time of concentration (Bhatt and Ahmed 2014), hence a detailed analysis of the basin is essential. The expert committee for flood analysis of 2019 floods appointed by the Government of Maharashtra recommended updating the reservoirs operation schedule (ROS) and to have an integrated reservoir operation schedule (Vadnere and Pawar 2019). It is essential to have exact site-specific conclusions and recommendations for the releases of dams in the Krishna basin in Maharashtra. The two-stage flood mitigation potential of reservoirs needs to be evaluated. The authors have executed the technical analysis of reservoirs, spills from them, and the impact of these spills downstream. The observed inflow and released outflow from dams and their response to downstream floods are analysed and discussed in detail for the reservoirs. The flood absorption capacity pre-flood and during the flood has been assessed. The impact on downstream of dam releases as well as free catchments has been studied in detail. Additionally, the study aims at analyzing the quantitative role played by three important dams in flood mitigation. The results of this work will help prepare an integrated reservoir operation schedule.

1. Study Area and Data River Network and Reservoirs

1.1 River Network in Krishna Basin

The study area as shown in Figure 1, is located between 17° 59' 18.8"N and 73° 38' 16.7" E to 16° 19' 51.5"N and 75° 53' 16.8" E comprises of Krishna River 282 km and its tributaries in Maharashtra.

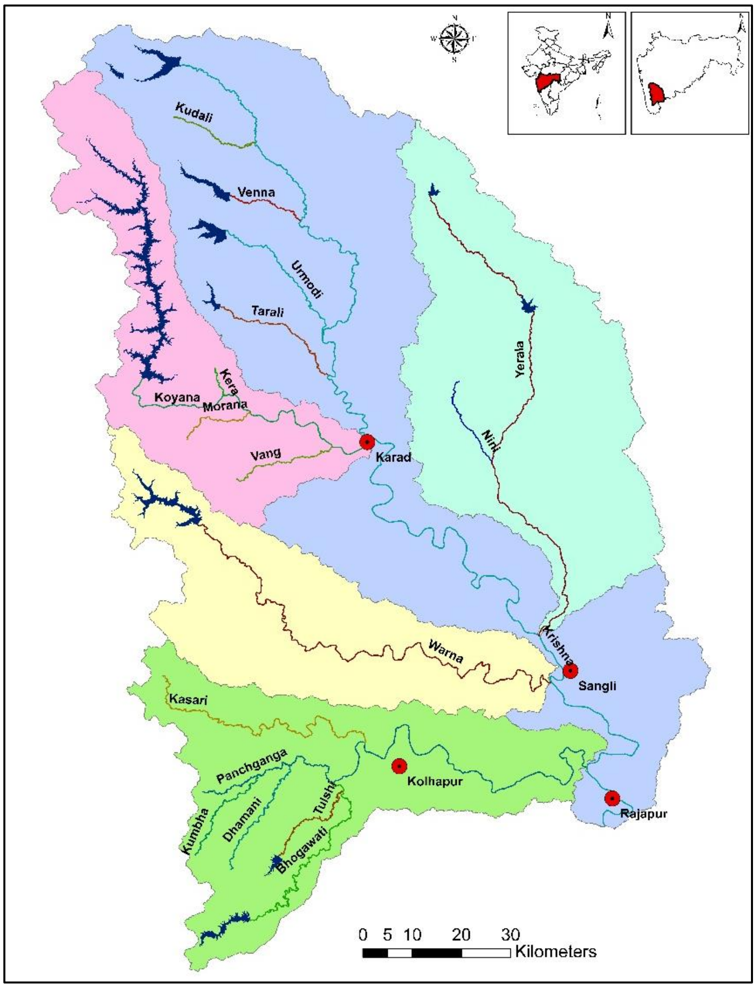

Fig. 1 Study Area and River Network in Krishna Basin in Maharashtra

The study area consists of the Krishna river in Maharashtra having a length of 282 km and a catchment area of 14270 km^2. Figure 1 shows the 22 tributaries on the Krishna river in the selected study area. Out of them, the main tributaries of the river Krishna are Koyna, Warna, and Panchganga. The confluence of Krishna with Koyna is at Karad, Warna is at Haripur (near Sangli), and Panchganga is at Rajapur (the last village on the bank of Krishna in Maharashtra state). The average bed slope of the Krishna river up to Karad is 1: 880, from Karad to Sangli is 1: 4113, and from Sangli to Rajapur is a gentle 1:4750. Warna River has a bed slope of 1:1450 in initial reach, and then 1:5411 for the last 57.63 km. Panchganga has a bed slope of 1:2529 in initial reach, and then 1:6345 for the last 93.74 km

1.2 Reservoirs in Krishna Basin within Maharashtra

There are 22 reservoirs in the Krishna basin, out of which 10 are major projects viz. Dhom, Kanher, Urmodi, Tarali, Koyna, Warna, Radhanagari, Dudhganga, Tembhu Barrage and Satpewadi Barrage. The 12 medium projects are Dhom-Balkawadi, Mahu, Uttarmand, Morna (Gureghar), Wang, Kadvi, Kasari, Kumbhi and Dhamani. The gross storage capacity of major and minor dams is about 6006.27 Mcum. The important features regarding the content of these reservoirs are enlisted in Table 1.

Table 1: Reservoirs in Krishna Basin in Maharashtra

Sr. No.	Name of Project / Dam	Gated or Ungated	Content Mcum			Content %	
			Content up to Crest	Against gates	Total	Content up to Crest	Against gates
1	Koyna	Gated	2072.13	908.02	2980.15	69.53	30.47
2	Dhom	Gated	248.21	134.05	382.25	64.93	35.07
3	Urmodi	Gated	167.21	114.88	282.02	59.29	40.73
4	Kanher	Gated	159.91	126.04	285.98	55.92	44.07
5	Dhom Balkawadi	Gated	94.73	20.78	115.53	82.00	17.99
6	Tarali	Gated	138.44	27.18	165.64	83.58	16.41
7	Yeralwadi	Ungated	32.85	-	32.85	100.00	0.00
8	Ner	Ungated	11.89	-	11.89	100.00	0.00
9	Wang	Gated	55.58	21.69	77.3	71.90	28.06
10	Morna (Gurheghar)	Gated	25.37	14.18	39.64	64.00	35.77
11	Uttarmand	Gated	16.64	8.278	24.92	66.77	33.22
12	Nagewadi	Ungated	6.51	-	6.51	100.00	0.00
13	Mahu	Gated	24.76	6.24	31	79.87	20.13
14	Hatgeghar	Ungated	7.36	-	7.36	100.00	0.00
15	Yevati Masoli	Ungated	7.3	-	7.3	100.00	0.00
16	Tulshi	Gated	73.98	24.29	98.27	75.28	24.72
17	Warna	Gated	766.66	207.36	974.04	78.71	21.29
18	Radhanagari	Auto Gated	236.71	-	236.71	100.00	0.00
19	Kumbhi	Gated	53.99	22.49	76.45	70.62	29.42
20	Kasari	Gated	54.08	23.86	77.87	69.45	30.64
21	Kadavi	Ungated	71.35	-	71.35	100.00	0.00
22	Morna (Shirala)	Ungated	21.24	-	21.24	100.00	0.00
Grand Total			4346.9	1659.338	6006.27	72.37	27.63

Table 1 shows that out of total storage of 6006.27 Mcum only 1659.338 Mcum (27.63 %) is against the gate on the dam which can be operated as and when required. This storage may contribute to the downstream flood situation or may be utilized in flood absorption. Major storage of 4346.9 Mcum (72.37 %) is below spillway crest. Three important reservoirs in the basin are Koyna, Warna and Radhanagari. The Koyna reservoir on the Koyna tributary is 67 km upstream of the confluence with Krishna and 175 km upstream of Sangli. The Warna dam is on Warna tributary 115 km upstream of Sangli. The Radhanagri dam is on the Bhogawati river, 73 upstream of Kolhapur and 141.5 km upstream of Rajapur. The Koyna dam, the largest in the basin has a live storage of 2980 Mcum, out of which 2072 Mcum (69.5%) is below spillway crest level and 908 Mcum (30.5 %) is against the gates. The reservoir operation can be performed only for this storage (which is against gates) and can be released by operating the gates. The remaining storage cannot be released.

1.3 Flood Prone area

The flood-prone area in the basin is shown in Figure 2. The first flood-prone location, Sangli is near the confluence with Warna. It receives water from the rivers Krishna, Koyna and Warna and the dams Koyna, Dhom, Dhom-Balkawadi, Kanher, Urmodi, Tarali, Yeralwadi, Ner, Wang, Morna (G), Uttarmand, Nagewadi, Mahu, Hatgeghar, Yevati Masoli, Warna, Morna (S). The farthest dam in this complex is the Dhom dam, which is 223 km upstream of Sangli. Koyna dam is 175 km upstream of Sangli. The next susceptible location is Kolhapur, which receives water mainly from the Bhogawati river and Radhanagari dam. It also receives water from Kasari, Kumbhi, Tulshi dams on respective rivers. Rajapur is located 38 km downstream of Sangli, which is the last village in Maharashtra on the Krishna River and is affected the most by floods. It receives water from all the above rivers and dams.

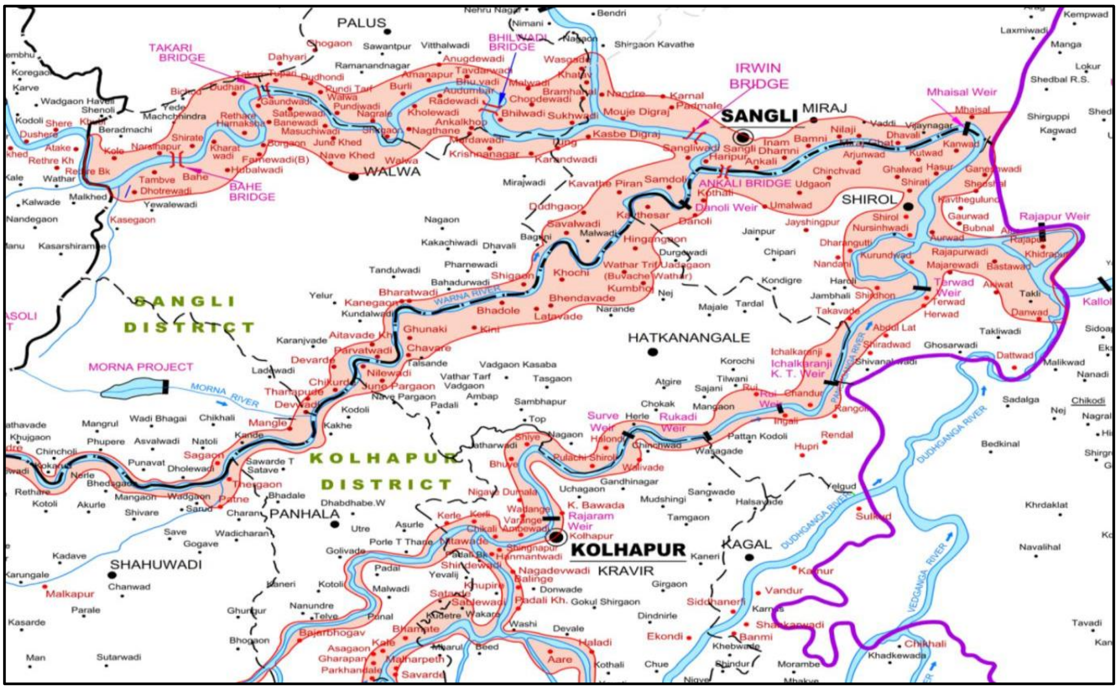

Fig. 2 Flood Prone Areas in Krishna basin

2.0 Methodology

The daily data from all reservoirs like inflow, outflow, the flood discharges at various flood-prone locations were collected. The time lag and travel time were applied for discharges at each location. The flood absorption capacity of each dam in Stage I and Stage II was assessed. Actual flood absorbed and utilisation of this capacity was analysed and presented. The observed discharges at Sangli, Kolhapur and Rajapur were bifurcated into dam release discharges and free catchment discharges and analysis was done. The conclusions regarding flood contributions were derived for these locations. An ideal condition (without upstream dams) was analysed at Rajapur and compared with observed floods. The role played by three important dams viz. Koyna, Warna and

Radhanagari in the flood period were analysed and their contribution to flood, flood absorption, reduction in peak discharge, and delaying the peak discharge was analysed and presented.

2.1 Travel Time of Flood

The data collected contains dam spill values and observed discharges at various locations. The dam spill values are real-time and the observed flood at Sangli, Kolhapur and Rajapur are also real-time. Thus, to bring them to a common time frame the travel time of dam releases for various locations were taken into consideration. The average travel times and distances in various river reaches are as shown in Table 2.

Table 2: Travel Times and Distances of various River Reaches

Sr. No.	River Reach	Distance (km)	Travel Time (hrs)
1	Dhom to Satara	45	8
2	Kanher to Satara	15	3
3	Satara to Karad	71	13
4	Koyna to Karad	68	9
5	Karad to Sangli	107	14
6	Warna to Sangli	115	17
7	Sangli to Rajapur	38	6
8	Kolhapur to Rajapur	68.5	12.5

3.0 Results and Discussions

3.1 Contribution of Discharges to 2019 floods from Free and Intercepted Catchment

To analyse and find whether the flood at Sangli, Kolhapur and Rajapur was due to dam releases or floods from free catchments of the Krishna basin. The contribution of floods was studied in detail along with their travel time at the aforementioned locations.

3.1.1 Contribution of Discharges at Sangli from Free and Intercepted Catchment

Sangli is located on the bank of Krishna just upstream of the Warna confluence. The sister city Miraj is downstream of this confluence. The catchment area up to Sangli is 9357 km^2, out of which 2711 km^2 (29 %) is dam intercepted and 6646 km^2 (71%) is free catchment. If rainfall distribution is uniform all over the catchment area, then flood contribution from the intercepted catchment and free catchment areas would be 29 % and 71 % respectively. Observed discharge contribution from the free catchment and discharge from upstream dam spills from 30th July 2019 to 17th August 2019 is tabulated in Table 3.

Table 3: Flood Discharges at Sangli from Free Catchment and upstream Dam Spills

Date	Total Discharge	Discharge From Upstream Dam Spills		Discharge from Free Catchment	
		Cumec	%	Cumec	%
30 July 2019	1107	2	0.10	1105	99.90
31 July 2019	2088	2	0.01	2086.00	99.90
01 August 2019	2039	167	8.19	1872.00	91.81
02 August 2019	2039	198	9.71	1841.00	90.29
03 August 2019	2283	388	17.00	1895.00	83.00
04 August 2019	2792	514	18.41	2278.00	81.59
05 August 2019	3728	1716	46.03	2012.00	53.97
06 August 2019	4712	4252	90.24	460.00	9.76
07 August 2019	5665	4536	80.07	1129.00	19.93
08 August 2019	5900	4610	78.14	1290.00	21.86
09 August 2019	6324	3967	62.73	2357.00	37.27
10 August 2019	5955	2692	45.21	3263.00	54.79
11 August 2019	5575	2870	51.48	2705.00	48.52
12 August 2019	4976	2073	41.66	2903.00	58.34
13 August 2019	4302	1788	41.56	2514.00	58.44
14 August 2019	3044	1180	38.76	1864.00	61.24
15 August 2019	2015	854	42.38	1161.00	57.62
16 August 2019	1552	1033	66.56	519.00	33.44
17 August 2020	1193	794	66.55	399.00	33.45
	Average		44.71		55.29

It is observed from Table 3 that, average discharge contribution is 44.71% from the upstream dam spills representing a catchment area of 29%. The average discharge contribution is 55.29% from the free catchment area of 71%. Daily discharges (Total, from dam spills and free catchments) at Sangli are plotted in Figure 3.

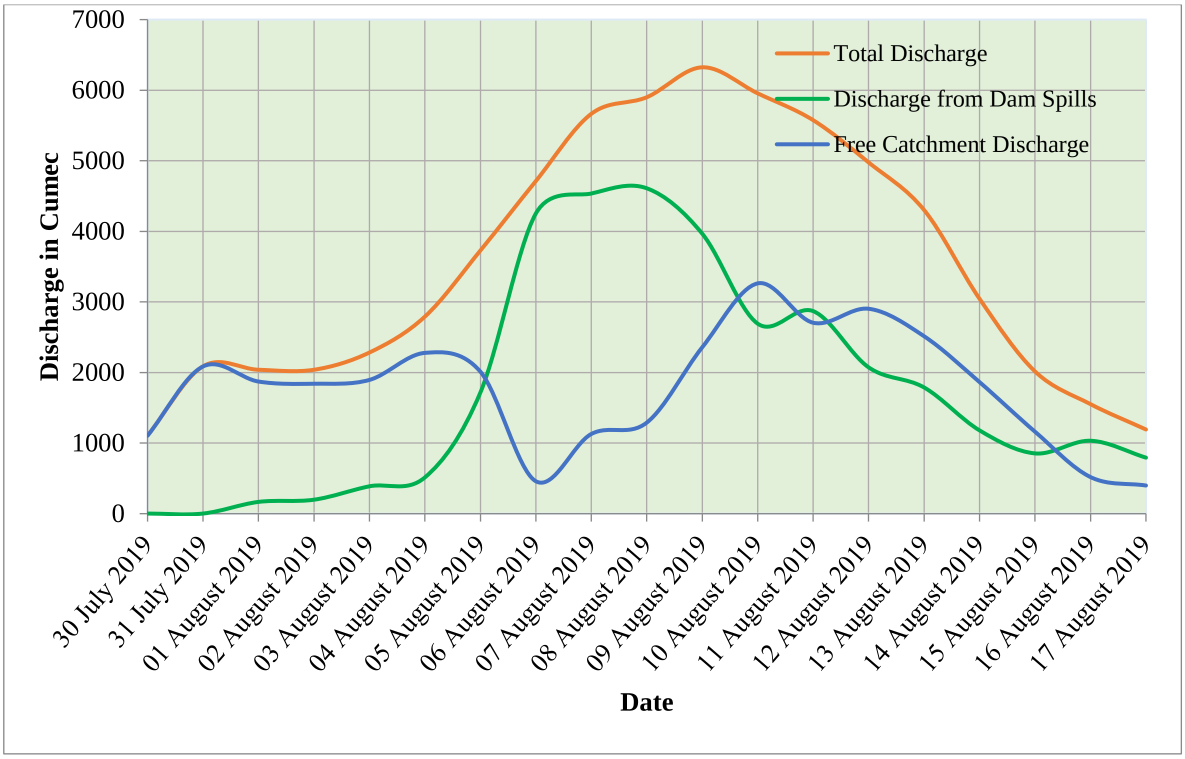

Fig. 3 Flood Discharges at Sangli from Free Catchments and upstream Dam Spills

Figure 3 shows that the peak discharge at Sangli was 6324 Cumec on 9th August 2019 and the most critical period was from 6th August 2019 to 13th August 2019. The discharge from dam spills contributed more towards the flood than the free catchment discharge from 6th August 2019 to 9th August 2019. For all remaining periods under consideration, the free catchment discharges contributed more. During these four days, the average flood value from dam spill discharges (which represents a catchment area of 29%), contributed to 77.95% of floods at Sangli. It can be safely deduced that for the critical period, the Sangli flood values were governed by the dam spill discharges. These releases were essential as all the upstream dams had achieved upper guide curves and it was dangerous to store more water in these dams. Due to the lack of accurate weather forecast, early releases (which might have mitigated the flood) were not possible.

3.1.2 Contribution of Discharges at Rajapur from Free and Intercepted Catchment

The total Catchment area at Rajapur is 14270 km^2. The dam intercepted catchment is 3317.26 km^2 (23%) and the free catchment is 10952.74 km2 (77%). Observed discharge contributions from the free catchment discharges and the upstream dam spills for the period of 30th July 2019 to 17th August 2019 are tabulated in Table 4.

Table 4: Flood Discharges at Rajapur from Free Catchment and upstream Dam Spills

Date	Total Discharge Cumec	Discharge From Upstream Dam Spills		Discharge from Free Catchment	
		Cumec	**%**	**Cumec**	**%**
30 July 2019	2583		0.00	2583	100.00
31 July 2019	4234	124	2.93	4110	97.07
01 August 2019	4533	298	6.57	4236	93.45
02 August 2019	4640	468	10.09	4173	89.94
03 August 2019	4868	727	14.93	4141	85.07
04 August 2019	5564	1025	18.42	4539	81.58
05 August 2019	6426	2626	40.87	3800	59.13
06 August 2019	7896	5708	72.29	2187	27.70
07 August 2019	8374	6230	74.40	2144	25.60
08 August 2019	9394	5762	61.34	3632	38.66
09 August 2019	9394	5114	54.44	4280	45.56
10 August 2019	9735	3481	35.76	6254	64.24
11 August 2019	9735	3508	36.03	6227	63.97
12 August 2019	9096	2748	30.21	6348	69.79
13 August 2019	8159	2333	28.59	5826	71.41
14 August 2019	6636	1261	19.00	5375	81.00
15 August 2019	5111	1041	20.37	4070	79.63
16 August 2019	4331	1203	27.78	3128	72.22
17 August 2019	3637	914	25.13	2722	74.84
	Average %		**30.48**		**69.52**

It is observed from Table 4 that, average discharge contribution is 30.48 % from the upstream dam spill discharge having intercepted catchment area of 3317 km^2 (23% area). The average discharge contribution is 69.52% from the free catchment area of 10953 km^2 (77% area). The daily flood data with discharge from the free catchment, from dam spills and total discharge at Rajapur, is as plotted in Figure 4.

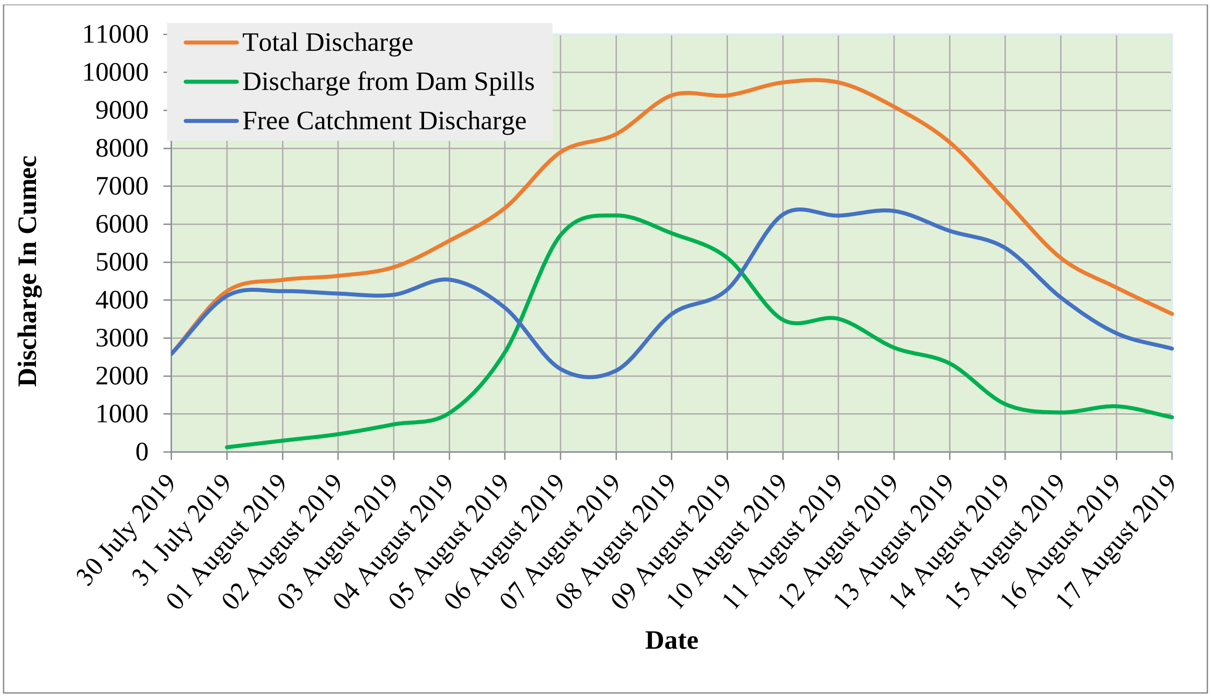

Fig. 4 Flood Discharges at Rajapur from Free Catchments and upstream Dam Spills

Figure 4 shows that the peak discharge at Rajapur is 9735 Cumec on 10th and 11th August 2019 and the most critical period was from 6th August 2019 to 13th August 2019. The discharge from dam spills contributed more towards the flood than the free catchment discharge from 6th August 2019 to 9th August 2019. For all remaining periods under consideration, the free catchment discharges contributed more. During these four days, the average flood value from dam spill discharges (which represents a catchment area of 23%), contributed to 66% of floods at Rajapur. It can be safely deduced that for the critical period, the Rajapur flood values were governed by the dam spill discharges. Also, the releases were essential from the safety point of view of dams. As in the case of Sangli, the early releases were possible but there was no firm support from the weather forecast.

3.1.4 Contribution of Discharges from Free and Intercepted Catchment at Kolhapur in 2019

Kolhapur is located on the bank of the Panchganga River. The catchment area till Kolhapur is 1606.2 km^2, out of which 197.2 km^2 (12 %) is dam intercepted and 1409 km^2 (88%) is free catchment. On similar lines to Sangli and Rajapur, observed total discharge, free catchment discharge, and dam spill discharge contribution at Kolhapur are tabulated in Table 5.

Table 5: Flood Discharges at Kolhapur from Free and Upstream Dam Spills

Date	Total Discharge	Discharge From Upstream Dam Spills		Discharge from Free Catchment	
		Cumec	%	Cumec	%
31 July 2019	1528	105	6.87	1423	93.13
01 August 2019	1732	105	6.06	1627	93.94
02 August 2019	1766	245	13.87	1521	86.13

03 August 2019	1791	152	8.49	1639	91.51
04 August 2019	1817	239	13.15	1578	86.85
05 August 2019	1872	330	17.63	1542	82.37
06 August 2019	1974	489	24.77	1485	75.23
07 August 2019	2111	728	34.49	1383	65.51
08 August 2019	2094	300	14.33	1794	85.67
09 August 2019	2026	501	24.73	1525	75.27
10 August 2019	2000	364	18.20	1636	81.80
11 August 2019	1964	327	16.65	1637	83.35
12 August 2019	1911	203	10.62	1708	89.38
13 August 2019	1847	162	8.77	1685	91.23
14 August 2019	1773	64	3.61	1709	96.39
15 August 2019	1482	75	5.06	1407	94.94
16 August 2019	1014	57	5.62	957	94.38
17 August 2020	903	57	6.31	846	93.69
	Average		13.69		86.71

It can be observed from Table 5 that the average discharge contribution was 13.96% from the upstream dam spills having intercepted catchment area of 197.2 km^2 (12% area). The average discharge contribution was 86.71% from the free catchment area of 1409 km^2 (88% area).

The daily flood data at Kolhapur is as plotted in Figure 5.

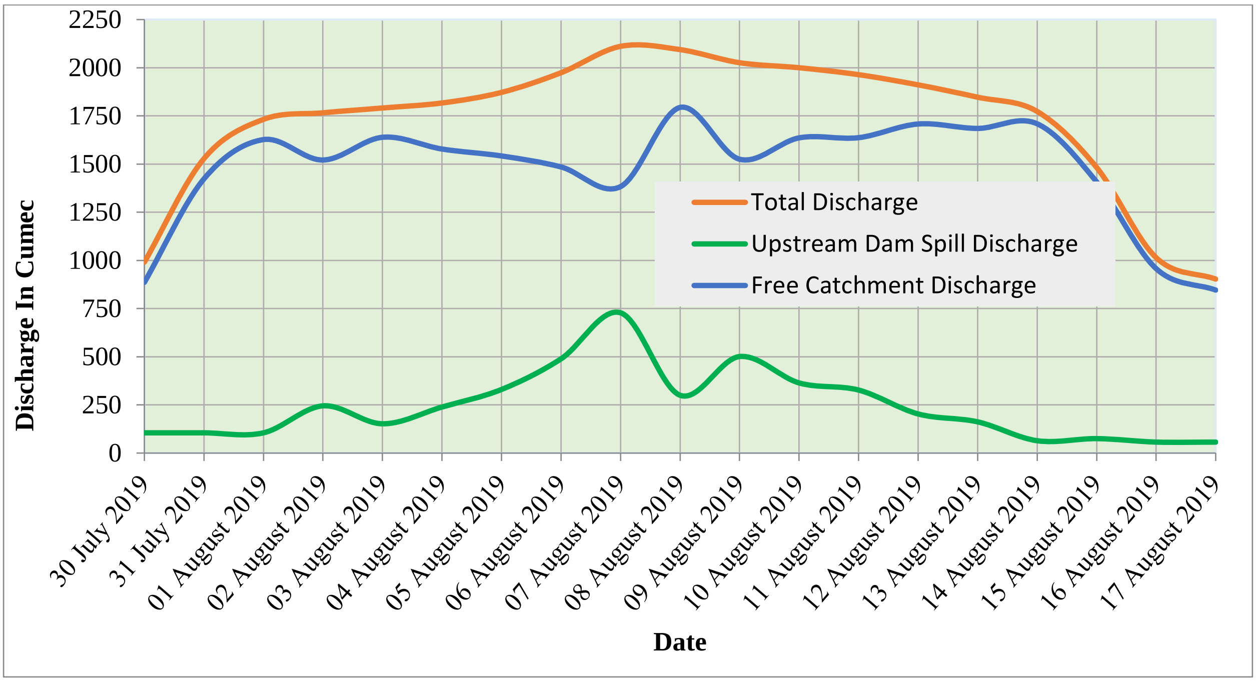

Fig. 5 Flood Discharges at Kolhapur from Free Catchments and Upstream Dam Spills

From Figure 5, it was found that the most critical period for Kolhapur was from 1st August 2019 to 13th August 2019. The contribution to floods from free catchment discharges was more than upstream dam spill discharges for all the time. Kolhapur flood values were governed by the free catchment floods and not by upstream dam spill discharges.

3.2 Flood Absorption in Dams

The flood absorption capacity of individual dams can be divided into two stages, the initial **Stage I** before outflow is started and later **Stage II** after dam spill starts. During Stage I, when reservoirs are empty, they absorb the entire flood, whether they have been designed for flood absorption or not. In this stage, the flood peak is diminished downstream. Stage II is when the reservoir achieves the crest level and storage against the gate and releases are possible. The inflow, outflow, corresponding dates, time lag, peak values are shown in Table 6 for ten important dams for the region.

Table 6: Flood Absorption by Dams in the Year 2019 in Krishna Basin

Sr. No.	Dam	Stage I: Before Outflow				Stage II: After Outflow Starts			
		Inflow Start Date	Outflow Start Date	Time Lag in Starting of Outflow	Quantity of Flood Absorbed	Peak Inflow	Peak Outflow	Reduction in Peak Flow	Time Lag in Peak Inflow and Outflow
				Days	Mcum	Cumec	Cumec	%	Days
1	Koyna	15-06-19	03-08-19	49	2072.13	5167	3507.00	67.87	2
2	Dhom	25-07-19	04-08-19	10	248.21	689.61	690.17	100.08	0
3	Urmodi	20-06-19	05-08-19	46	167.21	273.52	243.19	88.91	1
4	Kanher	10-07-19	30-07-19	20	159.91	717.08	509.43	71.04	0
5	Tarali	10-07-19	30-07-19	20	138.44	275.19	253.55	92.14	0
6	Tulshi	03-07-19	05-08-19	33	73.98	126.15	140.22	111.15	1
7	Warna	20-06-19	29-07-19	39	766.66	1192.91	969.39	81.26	2
8	Radhanagari	25-06-19	25-07-19	30	236.71	499.22	493.20	98.79	0
9	Kumbhi	20-06-19	27-07-19	37	53.99	77.37	111.96	144.71	1
10	Kasari	01-07-19	25-07-19	24	54.08	100.76	77.95	77.36	0
Total					3971.32	9118.81	6996.06	76.72	

Table 6 shows that the dam spills started after 25th July 2019. The total flood absorbed in all ten dams in Stage I is 3971 Mcum. The time lag between initial inflow and outflow of floods varies from 20 to 49 days. All the flood peaks are absorbed in Stage I. The major contribution to discharges at Sangli, Kolhapur and Rajapur are from Koyna, Warna and Radhanagari dams, these dams absorbed the initial floods for more than 30 days due to their storage capacity. In Stage II, when reservoirs achieved spillway crest levels, the outflows/releases were started. In most cases, the outflow values are lesser than the inflow values in the dams and there is a delay in the peak flood time. Thus, it can be inferred that there is flood absorption in Stage II as well. The outflow reduction of Koyna, Warna and Radhanagari was 33%, 29% and 19% respectively from 25th July to 17th August 2019 and the delay in peak flood is 0 to 2 days.

3.3 Flood analysis of "Without Upstream Dam Condition" at Rajapur

To study the impact of upstream dams in the Krishna basin, flood analysis was done as if there were no upstream dams at Rajapur. In such a case, inflow into the dams would have been converted directly into the outflow. Thus, discharges from dam intercepted catchments are derived by considering outflow equal to inflow. These flood values were added in free catchment discharges at Rajapur after applying travel time (Refer Table 2), to derive total "Without Upstream Dam Condition" discharges. This is compared with the observed flood and plotted in Figure 6.

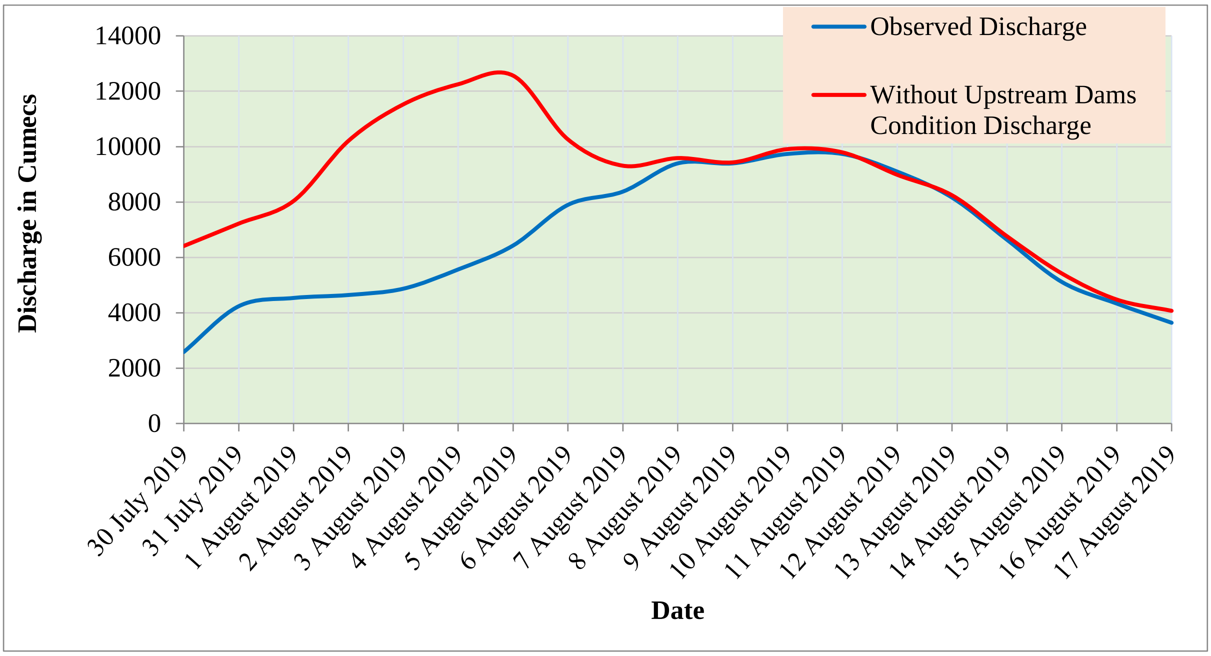

Fig. 6 With and Without Dam on Flood Discharges at Rajapur

From Figure 6, it can be seen that "Without Upstream Dam Condition" has much higher flood values than observed floods up to 8th August 2019. In this condition, the flood could have started on 2nd August 2019 at Rajapur, 4 days earlier than the actual flood. On 5th August 2019 the there was a peak discharge of 12564 Cumec in "Without Upstream Dam Condition" as against the observed discharge of 6426 Cumec. Which is almost two times the actual value. In other words, the upstream dams have mitigated Rajapur floods to 50%. After 8th August 2019, both discharges were almost the same for all days and neither flood mitigation nor flood intensification was caused by the upstream dams at Rajapur. Thus, the analysis proved that the upstream dams mitigated the flood at Rajapur by reducing and delaying the peak flood. Though these floods were governed by dam spill discharges, the impact was milder than the floods without upstream dams.

3.4 Role of Reservoirs during Floods in the Year 2019

The role and behaviour of the individual reservoirs are studied in the view of flood absorption. Three major dams i.e., Koyna, Warna and Radhanagari are analysed and presented here. Actual daily observed inflow and released outflows from dams are plotted to understand their effect on the downstream flood.

3.4.1 Role of Koyna Reservoir on Floods of the Year 2019

To analyse the role played by the Koyna dam in a flood situation, the daily inflow and outflow from Koyna dam for the period of 25 July 2019 to 15 August 2019 are compared and plotted in Figure 7.

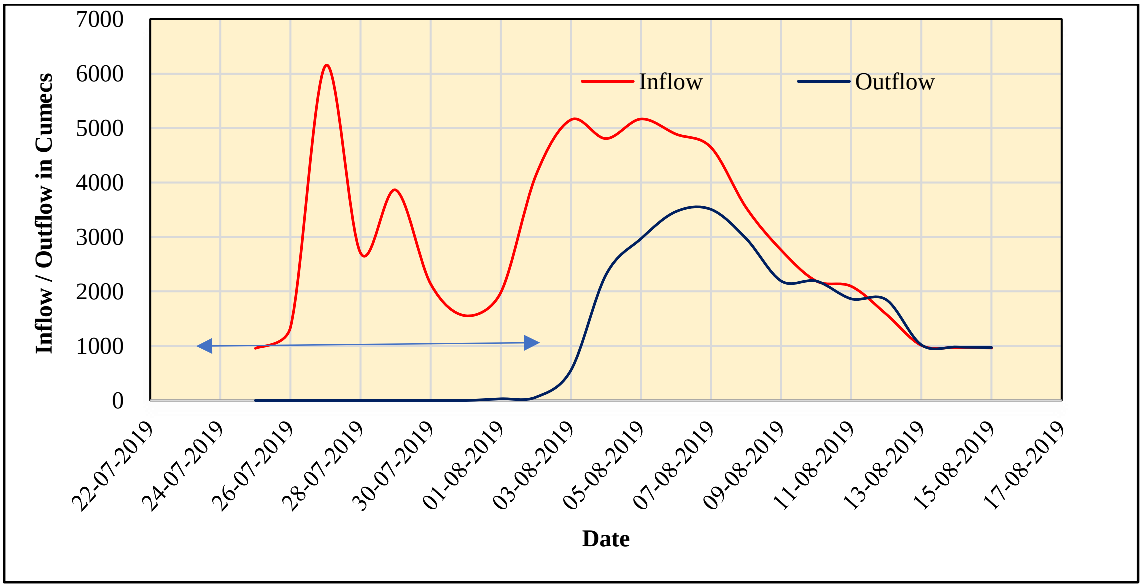

Fig. 7 Inflow and Outflow Flood Hydrographs at Koyna Reservoir

The Koyna dam played an important role in flood mitigation downstream. The actual inflow in the Koyna reservoir started on 15th June 2019 (Table 6). It can be observed from Figure 7 that, considerable inflow started in the Koyna dam on 25th July 2019 and the peak inflow of 6147 Cumec was observed on 27th July 2019. In the absence of the Koyna dam, this inflow would have created a flood situation in Sangli and Rajapur on 28th July 2019 and the situation would have been worse than the observed flood. The inflow was continuous, but the outflow was nil up to 4th August 2019 due to the storage capacity of the Koyna dam. In Stage I, the quantum of flood absorbed since the beginning of monsoon was 2072.13 Mcum. And the outflow from the dam was delayed by 49 days. In Stage II, after 4th August 2019, the maximum inflow observed was 5167 Cumec, however, the maximum outflow was 3507 Cumec. Thus, the peak was reduced by 32% due to the Koyna dam and outflow being delayed by 2 days thereby offering relief in the basin and helping in flood mitigation.

3.4.2 Role of Warna Reservoir in Floods During Floods of 2019

On a similar line to Koyna described in the previous section, the inflow and outflow at Warna dam are plotted in Figure 8.

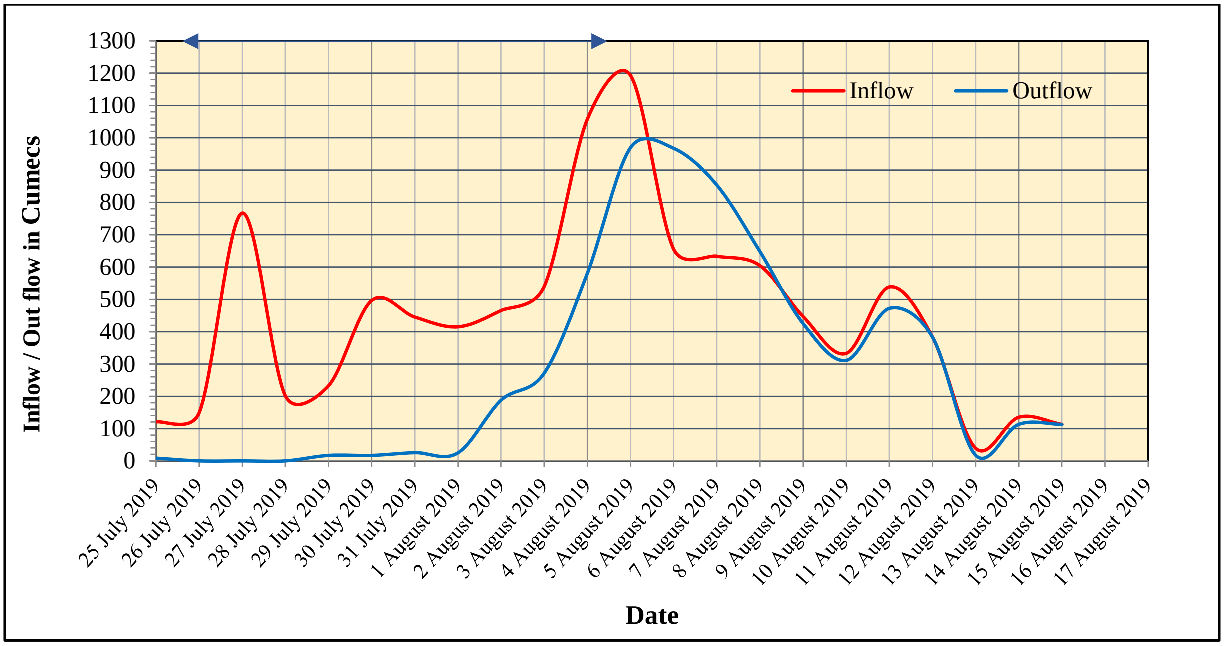

Fig. 8 Inflow and Outflow Flood Hydrographs at Warna Reservoir

The actual inflow in the Warna reservoir started on 20th June 2019 (Table 6). It can be observed from Figure 7 that, considerable inflow started in the Warna dam on 25th July 2019 and the peak inflow of 766.83 Cumec was observed on 28th July 2019. In the absence of the Warna dam, this inflow would have created a flood situation in Sangli and Rajapur on 29th July 2019 and the situation would have been worse than the observed flood. The inflow was continuous, but the outflow was nil up to 29th July 2019 due to the storage capacity of the Warna dam. In Stage I, the quantum of flood absorbed since the beginning of monsoon was 766.66 Mcum. And the outflow from the dam was delayed by 39 days. In Stage II, after 29th July 2019, the maximum inflow observed was 1193 Cumec, however, the maximum outflow was 967 Cumec. Thus, the peak was reduced by 19% due to the Warna dam and outflow being delayed by 2 days thereby offering relief in the basin and helping in flood mitigation.

3.4.3 Role of Radhanagari Reservoir in Floods during Floods of 2019

The Radhanagari dam has automatic gates, operated automatically on the reservoir water level. A plot of Radhanagari dam inflow and outflow is shown in Figure 9.

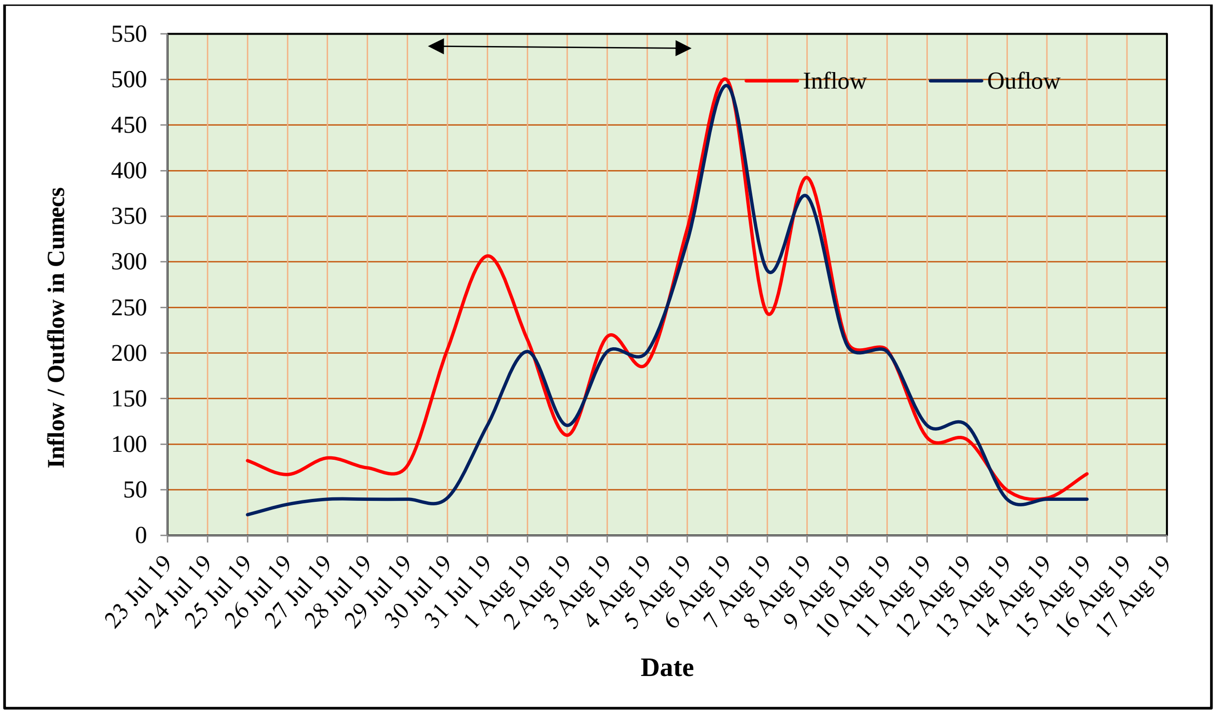

Fig. 9 Inflow and Outflow Flood Hydrographs at Radhanagari Reservoir

Figure 9 shows that in Stage I up to 31st July 2019, when the reservoir level was below the operation level of automatic gates, all inflow got accumulated in the Radhanagari dam. Thus, the dam absorbed a flood quantum of 236 Mcum in Stage I. The peak outflow was also reduced to 1/3rd of the inflow. However, in Stage II, this reservoir did not help in flood absorption. If this dam was equipped with control gates like Koyana and Warna this could have helped in flood absorption in Stage II as well.

Conclusions

1. The dams in the Krishna basin are not designed for flood absorption, however, they played important role in flood mitigation.
2. The flood mitigation by upstream dams can be divided into two stages. The first Stage I is the period up to reservoir water level archives spillway crest level and the second Stage II after water is stored/ released against the gates.
3. In the considered Krishna basin Only 28 % of total storage in 22 reservoirs are operable by gates. There is no control over the 72 % quantum of water that is below the crest. There is little scope for early depletion in predicted heavy rainfall situations. This could be overcome by developing the dam foot powerhouses and larger river sluices, etc. as flood control measures.
4. The worst flood situation in and around Sangli and Rajapur is governed by dam releases more as compared to free catchment runoff during the critical flood period from 6th to 9th August 2019. These releases were essential from the dam safety point of view as all the upstream dams had achieved upper guide curves. In absence of an accurate weather forecast, the early releases, which might have mitigated flood was not possible. Though these floods are governed by dam spills, the impact is milder than the case of floods without upstream dams. This can be mitigated by staggering the releases from various reservoirs. For staggering, temporary storage above guide curves in the existing dams may be allowed with safety

measures. The guide curves for dam releases in extreme flood situations should be modified from general guide curves.

5. The flood situation in and around Kolhapur is governed by free catchment floods and not from dam spill discharges. There is scope to propose/construct new dams upstream of Kolhapur for flood control measures.
6. It is suggested that the storage capacity against the gate could be increased in the Radhanagari dam by converting automated gates into control gates.
7. In Stage I, the quantum of flood absorbed is 3072 Mcum, and the floods are delayed by 20 to 49 days. Thus the upstream dams act as flood cushions for Sangli, Kolhapur and Rajapur areas.
8. In stage II, the Koyna and Warna dams the flood peaks were reduced by 32 % and 19 % respectively and flood peaks were delayed by 2 days.
9. “Without Upstream Dam Condition” would have created the almost twice adverse impact of the flood on flood-prone areas and floods would have occurred ealier.
10. Integrated Reservoir Operation Schedule should be designed for dams in the Krishna basin with revision in individual guide curves for flood control.

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