Reservoir management by rule curve

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ABSTRACT:

The dependability based rule curve was developed for Banasurasagar reservoir, by statistical analysis of historical daily inflow data. To create some dynamic flood cushion for moderating the floods of lower return periods, upper rule levels are derived from 50% dependable inflow series. Inflow hydrograph corresponding to rain with return periods 25, 50 and 100 year is derived and are routed through the reservoir at various upper rule levels and ensured that the reservoir does not surpass the FRL. It is also ensured that, at the end of monsoon, even when a PMF/SPF impinges the reservoir at the rule level, the MWL of the reservoir is not surpassed. As highly concentrated and extreme events are more common now, rule levels developed along with inflow forecast to the reservoir based on a quality rainfall prediction model shall be the basis for deciding the appropriate volume of water to be stored in the reservoir at each time step in advance. The upper rule curve is applied for various inflow series and found that the rule curve developed could best satisfy the objectives set for in an efficient manner.

1 INTRODUCTION

Kerala, the southern most state of India, has a wet and maritime tropical climate and receives rainfall mainly from two monsoons viz. southwest spanning from June to August and northeast spanning from September to November. In recent years, there is an increasing trend of extreme rain events in Kerala. Kerala witnessed an unprecedented rainfall during the southwest monsoon season of 2018. An abnormally high rainfall was experienced from June 1st to August 19th of 2018, which has led to devastating flash floods and landslides, nearly through the whole state. In managing reservoirs in these extreme conditions, the conventional methods of operation of reservoirs based on the experience of dam managers are often not adequate.

Reservoir operations for flood management play an important role in minimising damages to the downstream flood plains. Rule curve is a frequently used management technique for reservoir operation. On a specified date, a rule curve or rule level provides information about the storage or empty space to be maintained in a reservoir. In order to ensure maximum attenuation of the peak floods, it is imperative that maximum possible storage space is available in the reservoir when the floods approach the reservoir. The need to store water for the planned demands, however, presents a contradictory situation. Rule curve developed, based on detailed sequential analysis of various critical combinations of hydrological conditions and water demands is helpful in operating the reservoir in the most reliable and effective manner.

This study presents the dependability based rule curve developed for Banasurasagar reservoir in Kerala state, and demonstrates the application of rule curve in reservoir management for the year 2019.

2 METHODOLOGY

Rule curves are target levels to be maintained in the reservoir during different time periods of a year, under different conditions of inflows. For Banasurasagar reservoir, dependability based rule curve was developed by statistical analysis of historical daily inflow data. The details such as daily reservoir level, power house releases, spill details, scheduled generation from power house, derived inflow, elevation storage curves, elevation outflow curves etc. are collected for the period from 2006 to 2018.

Rule levels are derived from Mass balance equation, St+1 = St + Qt –Et - Dt – Rt, whereas St+1 is storage at the end of the period t and St is Storage at the beginning of the period t, Qt is inflow for the period t, Et is evaporation loss for the period t, Dt is power generation demand for period t and Rt is release for the period t.

Rule curve is developed for ten daily time step to eliminate the fluctuation in inflow. To create some dynamic flood cushion for moderating the floods of lower return periods, upper rule levels are derived from 50% dependable inflow series. Inflow hydrograph corresponding to rain with return periods 25, 50 and 100 year is derived and are routed through the reservoir at various upper rule levels and ensured that the reservoir does not surpass the FRL. It is also ensured that, even when a PMF/SPF impinges the reservoir at the rule level at end of monsoon, the MWL of the reservoir is not surpassed

3 PROCEDURE FOR DEVELOPING UPPER RULE LEVEL

Variables of mass balance equation are derived as follows.

From the historical data, the daily inflow to the reservoir is arrived. The cumulative inflow of 10 daily time step is calculated. 50% dependability inflow series is derived from historical ten-daily series. Variable Qt (MCM) is the 50% dependable inflow for that particular period. Variable Dt (MCM) is the release to power station corresponding to scheduled generation and Et (MCM) is the evaporation loss calculated based on reservoir water spread at respective reservoir levels.

Final storage (St+1) corresponding to the target reservoir level assumed at the end of monsoon (target date) is calculated as per the Elevation – Storage curve. The target reservoir level can be Full Reservoir Level or a level below FRL. The storage on the previous time step St is calculated from the equation St = St+1 – Qt+ Et + Dt +Rt. The elevation corresponding to the storage in the previous time step is obtained from elevation storage curve. This calculation is repeated till the first-time step, i.e., June 1-10 (beginning of monsoon), to derive the rule levels corresponding to 50% dependable inflow. The upper rule levels for each time step are derived from rule levels corresponding to 50% dependable inflow and by analyzing the historical behaviour of the reservoir water surface elevation in that time step. The derived rule levels are smoothened to one digit.

The rule levels derived for each time step are verified by the reservoir routing done by modified puls method for the various return period flood hydrographs. In order to develop the flood hydrographs of various return period rainfall, the catchment for the reservoir is delineated in the GIS platform and synthetic unit hydrograph for the catchment as per the Flood estimation report 5 (a) & (b) is developed. For deriving inflow hydrographs corresponding to rain with return periods viz. 25 year, 50 year, and 100 year, rainfall values are taken from PMP Atlas and inflow hydrographs of Banasurasagar catchment for different return periods are derived. Inflow hydrographs derived are routed through the reservoir at various upper rule levels. Ensured that the water level in the reservoir did not encroach the FRL after routing the derived inflow hydrographs for lower return periods at various time steps.

4 CASE STUDY

4.1 *Project Description*

Banasurasagar dam is the largest earthen dam in India, having a storage capacity of 209.18 MCM. It lies in Kerala, the southern most state of India. Banasurasagar reservoir is prone to frequent spilling in both the monsoon seasons.

Banasurasagar Dam is constructed, as part of Kuttiyadi Augmentation Scheme in 2005. This reservoir is created by constructing a homogeneous rolled earth fill type dam at Padinjarethara across Karamanthodu, a tributary of Panamaram River of Kabini. From the water stored in this reservoir, about 155.76 MCM is diverted to the Kakkayam Reservoir of 34MCM capacity through a diversion tunnel, for augmenting power generation and irrigation. A gate arrangement at the tunnel to control the flow of water from Banasurasagar reservoir or KA reservoir to Kakkayam reservoir is provided at the rear end of Banasurasagar reservoir. The overflow arrangement of the Banasurasagar reservoir is provided in a separate spillway Dam. The spill from this reservoir is

discharged through 4 nos of radial gates of size 10.97 m x 9.20 m. The spillway releases flow to Kabani River and empties in to Kabini reservoir in Karnataka State, located about 60 km downstream of spillway. Location of project is shown in figure 1.

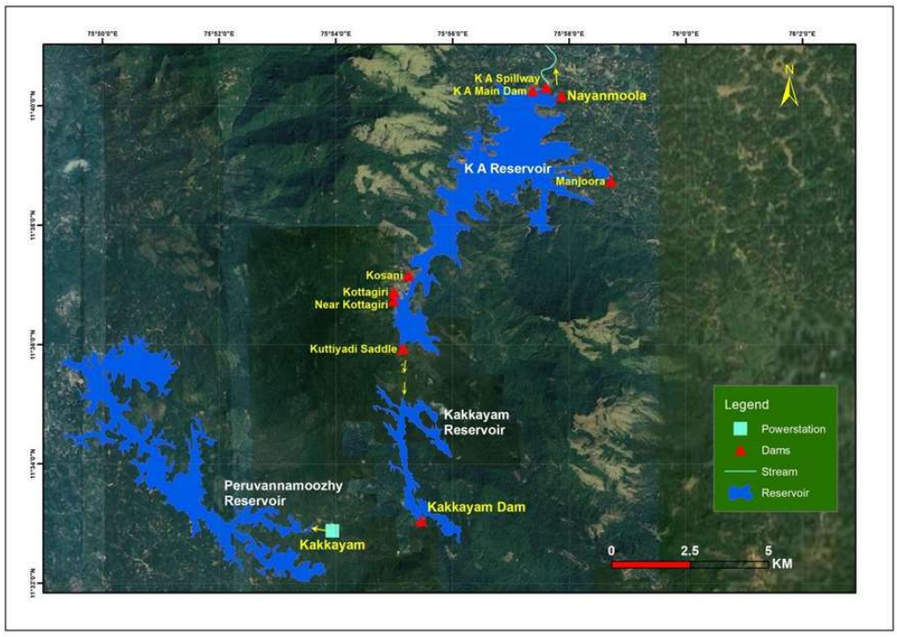

Figure 1. Location of Banasurasagar project

4.2 *Catchment area of the Project*

The location of the Banasurasagar dam is at latitude $11^0$40’15”N and longitude $75^0$57’21”E. The catchment area of the reservoir is 61.44 sq.km. The maximum hydraulic head and gross storage of the dam are 30.5m and 209.18 MCM respectively. As per BIS 11223-1985 criteria, the dam is classified as large dam and therefore qualifies for PMF as design flood. For estimating the Probable maximum flood and flood hydrograph of lower return period floods, synthetic unit hydrograph of Banasurasagar catchment is developed by delineating the catchment in GIS platform. The catchment area map and unit hydrograph are shown in figure 2 and figure 3 respectively.

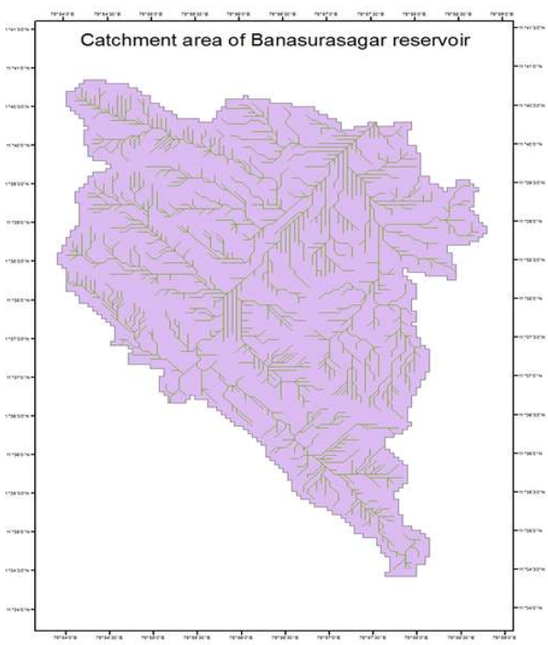

Figure 2. Catchment area of Banasurasagar reservoir

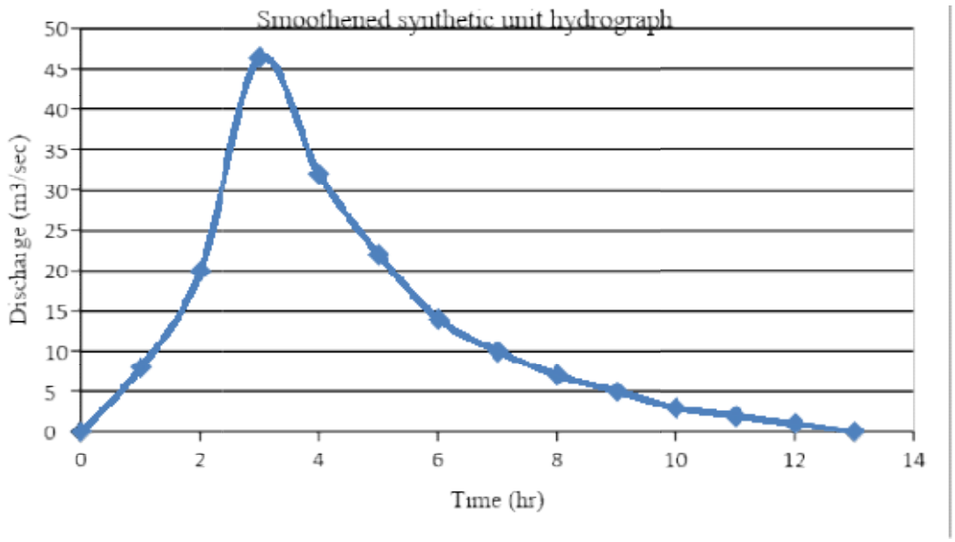

Figure 3. Unit hydrograph of Banasurasagar catchment

4.3 *Analysis of historical behaviour of Banasurasagar Reservoir*

The monsoon in Kerala is divided into two monsoons viz. southwest spanning from June to August and northeast spanning from September to November. In Kerala, in general, the months from June to August receives about 65% of the total monsoon rain-fall. But, by observing the rainfall pattern in Banasurasagar catchment over the years, it is evident that about 80% of the total monsoon rainfall of the catchment is received in June to August ie in Southwest monsoon. In North east monsoon season ie from September to November, only 20% of total monsoon rainfall is received in the catchment. Rainfall pattern in Banasurasagar dam catchment in various years is shown in figure 4.

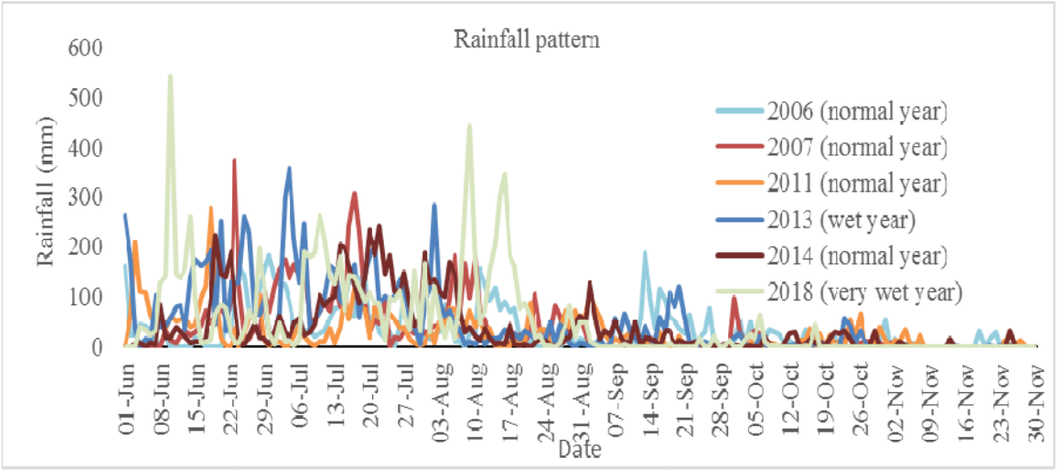

Figure 4. Rainfall pattern of Banasurasagar dam catchment area

From the historical inflow data of the period from 2006 to 2018, statistical analysis is done and the years are classified into dry years, normal years, wet years and very wet years based on the drought indices. The behaviour of the reservoir during various significant years such as 2018 (very wet year), 2014 (normal year), 2013(wet year) and 2011(normal year) are shown in figure 5.

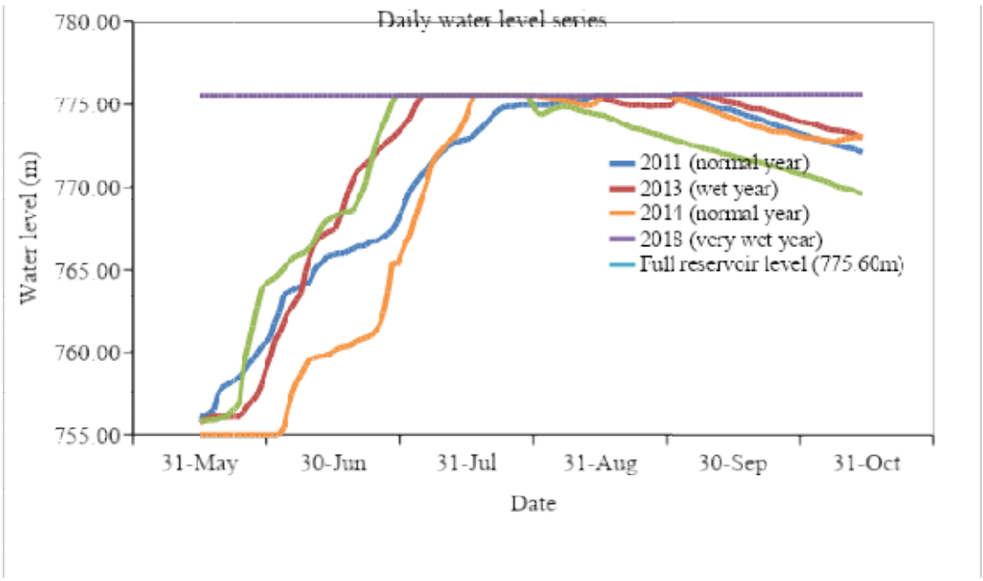

Figure 5. Reservoir behaviour of various years

It is observed that, in wet years and even in normal years, banasurasagar reservoir attains its full reservoir level in the end of southwest monsoon itself.

4.4 *Deriving rule levels*

From the analysis of the historical behaviour of Banasurasagar reservoir, it is evident that, 80% of the total monsoon rainfall in this catchment is received in the period from June to August and the reservoir attains its full reservoir level by the end of southwest monsoon season. As 20% of total monsoon rainfall is received in north east monsoon season i.e from September to November, the target level is fixed judiciously as 0.60m below FRL, i.e 775.00m, to impart a dynamic cushion for flood absorption in the reservoir and for accommodating the rainfall in North east monsoon season. It is ensured that, at this level, when a PMF impinges the reservoir, it will not surpass MWL/FRL.

As banasurasagar catchment receives 80% of its total rainfall in southwest monsoon itself, it is decided to adopt the target date, the date on which the reservoir is allowed to attain its target level 775.00m as 20th September, for deriving the Rule levels for the earlier time steps. From the storage corresponding to target level 775.00 m on September 20th, the storage at previous time steps are worked out for the inflow corresponding to 50% dependable inflow.

Table 1. Rule levels corresponding to 50% dependable inflow

Date	Rule Storage	Rule Level	50%dependable inflow	50%dependable Tunnel discharge
	Mm3	m	Mm3	Mm3
June 10th	26.20	755.43	5.090	10.290
June 20th	36.90	757.38	20.990	10.290
June 30th	46.40	758.99	19.790	10.290

July 10th	60.00	760.94	23.890	10.290
July 20th	69.20	762.22	19.490	10.290
July 31st	99.20	765.71	41.318	11.318
Aug 10th	130.60	768.82	41.690	10.290
Aug 20th	151.20	770.71	30.890	10.290
Aug 31st	168.80	772.23	28.918	11.318
Sep 10th	197.60	774.64	39.090	10.290
Sep 20th	202.00	775.00	14.690	10.290

4.5 Upper rule levels

The upper rule levels for the period from June 1st to September 20th is arrived at by setting the target level in the reservoir on September 20th as 775.00m. The target level in the initial time step is taken as 767m (Crest Level of spillway -767m). From the rule levels corresponding to 50% dependable inflow as well as the peaks in the historical water levels, the intermediate upper rule levels are judiciously arrived. Reservoir is allowed to rise up to FRL (ie 775.60m) only on Oct 20th. The storage corresponding to rule level and the flood space available at respective levels is shown in the table 2.

Table 2. Upper Rule levels of Banasurasagar reservoir

Time Step	Date	Upper Rule Levels	Rule storage	Flood space upto FRL	Percentage Gross Storage
		m	Mm3	Mm3	%
1	June 10th	767.00	112.00	97.25	53.5%
2	June 20th	767.00	112.00	97.25	53.5%
3	June 30th	768.00	121.60	87.65	58.1%
4	July 10th	771.00	154.60	54.65	73.9%
5	July 20th	773.50	183.60	25.65	87.7%
6	July 31st	773.50	183.60	25.65	87.7%
7	Aug 10th	774.00	189.90	19.35	90.8%
8	Aug 20th	774.50	195.80	13.45	93.6%
9	Aug 31st	774.50	195.80	13.45	93.6%
10	Sep 10th	775.00	202.00	7.25	96.5%
11	Sep 20th	775.00	202.00	7.25	96.5%
12	Sep 30th	775.00	202.00	7.25	96.5%
13	Oct 10th	775.00	202.00	7.25	96.5%
14	Oct 20th	775.60	209.25	0.00	100.0%
15	Oct 31st	775.60	209.25	0.00	100.0%

4.6. Routing with flood hydrographs

The full reservoir level of Banasurasagar dam is 775.60m. Maximum water level is same as FRL. The spillway discharge capacity at FRL is 1664m^3/sec.

For deriving the design flood hydrograph, one day PMP of 57.60 cm is adopted as design storm from PMP Atlas. The peak of deign flood is obtained as 1275m^3/sec. As design flood is within the spillway capacity, it can be easily discharged through spillway.

To accommodate the rainfall in North east monsoon season, the upper rule level, from September 10th to October 10th, is maintained at 0.60m below FRL i.e at 775.00m. Even when PMF impinges reservoir at 775.00m, it will not surpass the FRL/MWL.

To validate the upper rule levels fixed for each time periods, inflow hydrographs of lower return periods viz. 25 year, 50 year and 100 year return period floods are developed and reservoir routing using Modified puls method done.

Rainfall of 36.00 cm is adopted as 100 year return period one day annual maximum rainfall from PMP Atlas. The peak of 100 year return period flood hydrograph is obtained as 668.00 m3/sec. When this flood hydrograph is routed through the reservoir with impingement level as 775.00 m, it is found that the reservoir level is not encroaching the FRL after allowing a spill of 111.00 m3/sec. The inflow – outflow hydrograph is plotted in figure 6 and it is observed that the magnitude of spill is reduced and dispersed over a period of time.

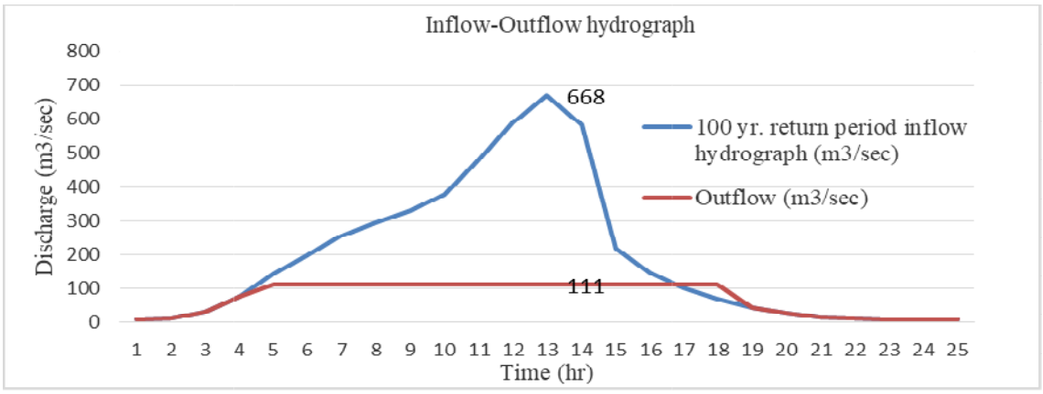

Figure 6. Inflow-Outflow hydrograph

The variation in reservoir water level elevation during reservoir routing of a 100 year return period flood hydrograph with impingement level at 775.00m is shown in figure 7.

It is evident that even when a 100 year return period flood impinges the upper rule levels in monsoon period, it is possible to utilize the dynamic flood cushion between rule level and FRL and thereby to minimize the flooding havoc of downstream areas.

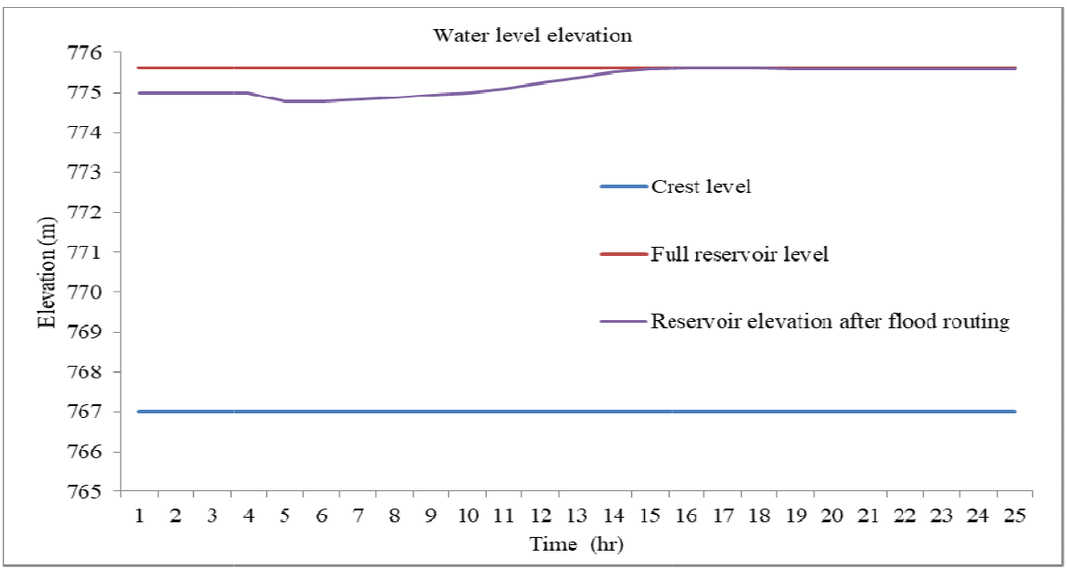

Figure 7. Reservoir water level elevation of a 100 year return period flood hydrograph

5 APPLICATION OF RULE CURVE IN THE YEAR 2019

Rule curve developed for the Banasurasagar dam is applied for the banasurasagar reservoir management in the year 2019. The reservoir management done using the rule curve is depicted in figure 8. Inflow – Outflow graph of the reservoir for the year 2019 with the application of rule curve is plotted and shown in figure 9.

From the figures it is evident that when the reservoir is operated by applying the rule curve during the critical period of inflow, the inflow is greatly attenuated and peaks that would have occurred in the spill discharge is eliminated. Thus rule curve developed for the Banasurasagar reservoir could best manage the reservoir during the monsoon seasons.

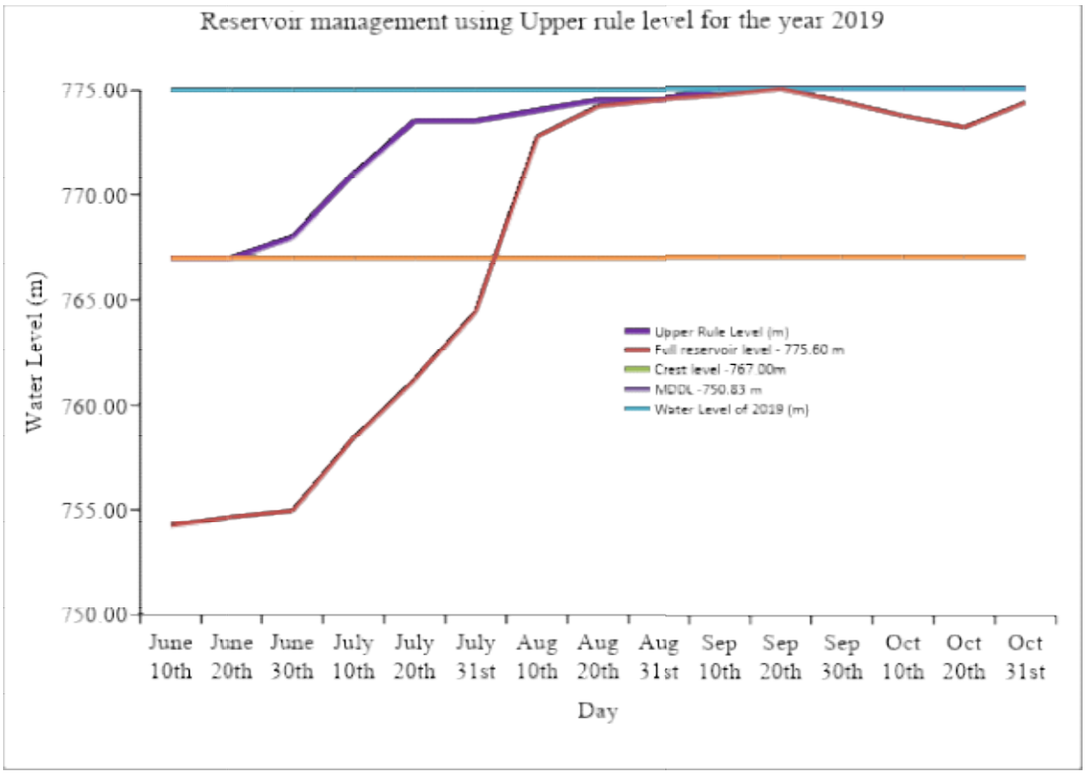

Figure 8. Reservoir levels 2019 and Upper Rule curve

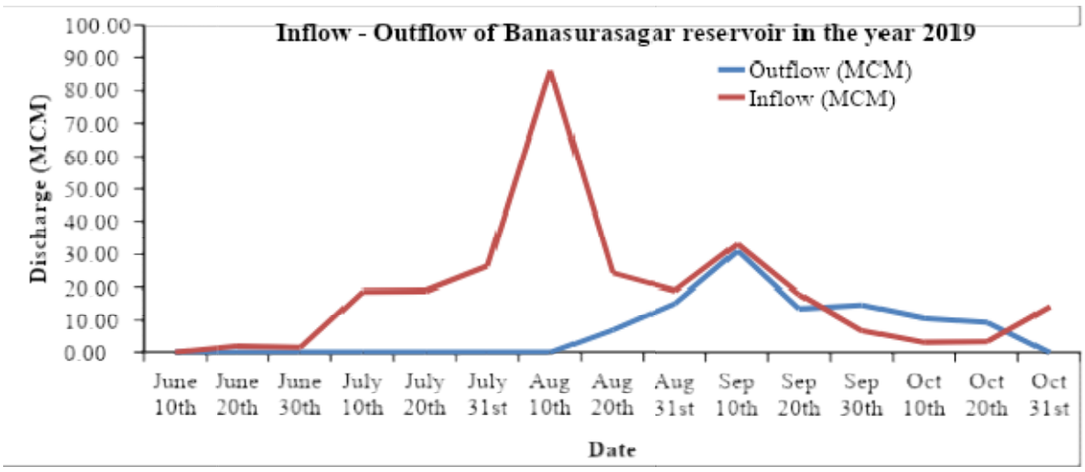

Figure 9.Inflow and Outflow of Banasurasagar reservoir on 2019

5 CONCLUSION

The rule levels may be used as a guide line to plan in advance the appropriate volume of water to be stored in the reservoir at each time step for satisfying operational objectives including dam safety, flood mitigation, achieving sufficient end-of-operation storage for conservation purposes and smooth operation. The storage and inflow to the reservoir has to be reviewed at every time step and appropriate strategy is to be evolved based on the inflow forecast. It may be tried to keep the reservoir level near to rule levels by adopting appropriate operation strategy.

As highly concentrated and extreme events are more common now, meticulous planning is necessary for effective operation of the reservoir. Rule Levels at various time steps along with inflow forecast to the reservoir based on a quality rainfall prediction model shall be the basis for deciding the appropriate volume of water to be stored in the reservoir at each time step in advance.

Rule levels are not hard and fast levels and shall not be followed blindly; instead it shall be used as a guide line for making prudent decisions for the effective operation of the reservoirs, depending up on the hydro-meteorological status of the basin then and there, especially in case of occurrence of extreme flood / drought events.

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