Evaluation of Hydrological Safety of Sholayar Dam

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Abstract—The construction of dams in rivers can offer many advantages; however, the consequences resulting from their failure could result in major damage, including loss of life and property destruction. To mitigate the threats of dam break it is essential to appreciate the characteristics of the potential flood in realistic manner. In the present study, it is proposed to estimate the revised flood of Sholayar dam of Kerala using the updated PMP Atlas published by Central Water Commission and the synthetic unit hydrograph developed based on the Flood Estimation Report published by Central Water Commission in HECHMS plat form. It is also trying to rout the flood through reservoir as well as river reach when inflow design flood impinges the reservoir during FRL condition using HEC-RAS. Adequacy of spill way to handle the revised inflow design flood is also studied.

Index Terms—Central water commission method, Delineation, Flood hydrograph, Flood routing, HEC-HMS, HEC-RAS, Probable maximum flood,

1 INTRODUCTION

Any public civil work facility such as dams, buildings or bridges present a degree of risk to loss of life or damage to property should it fail. All such structures also have the characteristics to change over time in adjustment to their surroundings and in their surroundings and in their capability to resist the forces imposed upon them by man and nature. Dams however, due to the ever-changing conditions of the populations located along the riverbanks downstream, often constitute a higher hazard in case of failure than other public structures. The life of dam can be threatened by natural phenomena such as floods, earthquake, rockslides and deterioration of heterogeneous foundations and construction materials. In the course of time, the structure may take on anisotropic characteristics. Internal pressure and paths of seepage may develop. Usually the changes are slow and not readily discernible by visual examinations. Most of the failure of dams in India is reported by Dam Rehabilitation and Improvement Project (DRIP) to be due to overtopping, especially overtopping due to inadequate capacity of the spillways or malfunctioning of spillway gates.

Nowadays, the extreme rain fall events are occurring more frequent across Kerala. Flood events were occurred consecutively during 2018 and 2019. In this scenario, the safety of the existing dams is to be evaluated with updated data and guidelines. Examination of revised design flood studies carried out for a set of 94 dams under World Bank funded 'Dam Rehabilitation and Improvement Project (DRIP)' by Central Water Commission reveals that the design flood values have increased substantially with trends indicating that percentage increases in the revised design flood values are more for older dams.

Sholayar dam was commissioned in 1965. Full Reservoir Level of the Sholayar reservoir is 811.68. Top level of dam is 812.60. The inflow design flood as per the project proposal was 1710 m3/s. Inflow design flood was estimated using Ryves empirical equation. In this study, the inflow design flood of Sholayar reservoir was estimated complying with BIS 11223 & updated PMP Atlas published jointly by Central Water Commission and Indian Meteorological Department to review the hydrological safety of Sholayar dam. Unit Hydrograph approach was adopted here, and HEC-HMS software is used to generate the flood hydrograph. HEC-RAS software is used for flood rooting.

1.2 Objectives

1. To find revised design flood and to check Hydrologic Safety of dam with probable maximum flood using HEC-HMS
2. Reservoir routing of flood hydrographs with PMF by modelling the system with HEC-RAS.
3. To study the structural and non-structural measures to handle increased design flood

1.3 Scope

Failures are mostly caused due to hydrological inadequacies of dam. In this paper mainly attempted to evaluate the hydrological safety of sholyar dam which is constructed more than five decades back.

2 STUDY AREA

Sholayar Project is in Thrissur District. The project is accessible from Chalakudy through State Highway 21. Project location is about 70 km from Chalakudy. Nearest railway station is Chalakudy. Nearest airport is Cochin International Airport. The study area includes the catchment area of Sholayar dam and downstream reaches of Sholayar dam up to Poringalkuthu. Sholayar stream originate from Tamil Nadu. Sholayar confluences with Chalakudy river about 15 Km downstream of Sholayar dam. The geographical coordinates of main dam are at Lat: 100 19' 19" N & Long: 760 44' 07".

3 DATA AND METHODOLOGY

3.1 Data

The following data & reference documents are collected as part of the study.

1. Characteristics of reservoir: Elevation storage table, Elevation out flow details and characteristics of dam.
2. Storm details: Storm details are taken from PMP Atlas

published by Indian Meteorological Department & Central Water Commission in 2015.

3. Terrain data: The digital elevation model (DEM) derived from the Japan Aerospace Exploration Agency (JAXA) global digital surface model (DSM) dataset with a horizontal resolution of approximately 30 meters (1arc-sec) (Takakuet al. 2014) is used to derive catchment characteristics of basin and flood plain modelling of downstream

4. Land Use Land Cover data: Glob Cover 2009 v2.3 dataset developed by the European Space Agency (ESA) was used to estimate the Roughness coefficients of the hydraulic model.

5. Flood Estimation Report 5 a &b: Flood Estimation report prepared by Central Water Commission is used for deriving unit hydro graph and generating flood hydro graph. Unit hydro graph parameters are worked out based on the equations for the catchment of West flowing Rivers.

6. Indian standard specifications for fixing spillway capaci ty: The criteria for design flood estimation are taken based on the IS 11223.

7. Softwares used,

- HEC-Geo HMS integrated with Arc GIS is used for delineating catchment & determining catchment parameters.
- MS Excel is used for deriving unit hydrograph, effective hourly unit rainfall from one day PMP.
- HEC-HMS is used deriving flood hydrograph from design storm.
- HEC-RAS is used for reservoir routing and channel routing downstream.

3.2 Methodology

3.2.1 Delineation of Catchment Area

A catchment is the area of land where all of the water that falls in it and drains off of it goes into the same place or common outlet. The catchment area of Sholayar dam is delineated using HEC- Geo HMS integrated with Arc GIS.

In simple words catchment is a region of land within which water flows down into a specified body, such as a river, lake, sea, or ocean, a drainage basin. Catchment analysis refers to the process of using DEM and raster data operations to delineate catchments and to derive features such as streams, stream network, catchment areas, basin etc.

3.2.2 Generating Synthetic Unit Hydrograph

Unit Hydrograph of the catchment is developed based on the 'Flood Estimation Report for West Coast Region - Konkan and Malabar Coasts Subzones – 5a & 5 b' published by CWC. This is more simple and accurate method to find the unit hydrograph, which require only limited data. The most important component of the procedure is finding out the unit hydrograph ordinates from a set of parameters. The parameters are to be found out through a set of equations derived from physical characteristics of the basin viz. area (A), length of the main stream (L), length of the main stream from the point opposite to the center of gravity of the basin (Lc), and equivalent slope of the basin (s). The ordinates of hydrograph are derived as per the equations given below,

Sl.	Parameter	Description	Equation
1	Qp	Peak discharge of Unit hydrograph	$0.9178(L/S)^{-0.4313}$
2	Tp	Time from the centre of rainfall excess (1.0 cm) in 1 hr unit duration to the unit hydrograph peak in hours	$1.5607(q_p)^{-1.0814}$
3	W50	Width of uunit hydrograph measured at 50% of peak discharge ordinates	$1.925(q_p)^{-1.0896}$
4	W75	Width of unit hydrograph measured at 75% of peak discharge ordinates	$1.0189(q_p)^{-1.0443}$
5	WR50	Width of rising limb unit hydrograph measured at 50% of peak discharge ordinate	$0.5788(q_p)^{-1.1072}$
6	WR75	Width of rising limb unit hydrograph measured at 75% of peak discharge ordinate	$0.3469(q_p)^{-1.0538}$
7	T_B	Base width of unit hydrograph	$7.38(t_p)^{0.7343}$
8	Tm	Time from the start of rise to the peak of unit hydrograph	$t_p+t_r/2$
9	Qp	Peak discharge of Unit hydrograph	q_p X A

3.2.3 Estimation of Design storm

Storage of Sholayar reservoir is 153 Mm3. Height of Sholayar Dam from deepest foundation is 66m. As the height of the is more than 30 m & Storage greater than 60 Mm^3, the project qualifies for PMF and the design storm will be PMP as per BIS 11223.

In the PMP Atlas, the nearest grid point to the catchment with higher one day rainfall value is WF 101-07 and PMP at that point s 524 mm for an area of 200 km^2 and considered for deriving inflow design flood. A design loss rate of 0.1 cm /hour as recommended by CWC in FER for subzone 5 a & 5 b for Western Coast Region has been adopted for estimating rain fall excess.

3.2.4 Design Flood Hydrograph using HEC-HMS

Flood hydrograph is derived using HEC-HMS. A total of six, unit hydrograph models are provided in the HEC-HMS program. These are (i) Clark unit hydrograph, (ii) ModClark unit hydrograph, (iii) SCS unit hydrograph, (iv) Snyder unit hydrograph, (v)

User-specified S-graph and (vi) User-specified unit hydrograph. Based on parameter requirement User-specified unit hydrograph methods have been selected in this study.

Different components included in the HEC-HMS are listed below.

- Basin Models: The physical basin area with hydrologic elements (subbasins, junctions, reach, reservoirs) and drainage network of the catchment are included in basin models.
- Meteorological Models: Information regarding meteorological components such as temperature, precipitation evapotranspiration, sunshine, humidity, snowmelt is defined in meteorological model. HEC-HMS provides variety of options to define each meteorological element.
- Control Specification: Starting date and time, ending date and time and computational time step for the simulation are defines in control specification.
- Timeseries Data: Real time series data for all the meteorological elements defined in meteorological model are fed in this part. Apart from above mentioned meteorological element, discharge data can also be supplied for calibration and simulation of the developed model. It can be supplied to the software manually or in the form of HEC-DSS, the Hydrologic Engineering Center Data Storage System.
- Paired Data: Meteorological data in tabular/graphical form are supplied as paired data.

Data required in HEC HMS: - Unit hydrograph, Design storm. Base flow: As recommended in CWC FER for subzone 5a & 5b, a base flow of 0.15 m3/s/sq.km has been considered.

3.2.5 Reservoir routing

Reservoir routing is used to determine the peak flow attenuation that a hydrograph undergoes as it enters a reservoir or other type of storage pool. Input data needed for storage routing include the inflow hydrograph and reservoir characteristics.

An Unsteady flow model of Sholayar Reservoir and its downstream flood plain is modeled in HEC-RAS with Terrain data, LULC data, Elevation – storage of reservoir, Elevation –Outflow, inflow design flood as inputs.

Reservoir routing is carried out with the following modules.

- RAS Mapper: Using the HEC-RAS geometry and computed water surface profiles, inundation depth and floodplain boundary datasets are created through the RAS Mapper. Terrain & Land Use Land Cover data added as layers in RAS MAPPER. The projection is set as WGS 1984 -UTM Zone 43N
- Geometric data: Using Geometric Data Editor Storage area, 2D Flow area, 2D flow area / Storage area connection etc. are created. Cell size of 100m X 100m considered for 2D flow area. Details of dam (X, Y values of the end of the dam) and spillway gates (Station, size & crest level of gates) are provided in Storage area- 2D Flow area connection. Downstream boundary line is drawn at the confluence of the river with the Poringalkuthu reservoir.
- Unsteady Flow data: The user is required to enter boundary conditions at all of the external boundaries of the system, as well as any desired internal locations, and set the initial flow and storage area conditions at the beginning of the simulation. The boundary condition for Storage area is Lateral Inflow Hydrograph. The downstream boundary of 2D Flow area is normal depth. Boundary condition at connection is Elevation Controlled Gates. Initial condition of reservoir is kept as FRL.
- Unsteady Flow Analysis: Once all of the geometry and unsteady flow data have been entered, the user can begin performing the unsteady flow calculations. The Computation Settings area of the Unsteady Flow Analysis window contains: the computational interval; hydrograph output interval; detailed output interval; the name and path of the output DSS file, and whether or not the program is run in a mixed flow regime mode. The computation interval is used in the unsteady flow calculations.

Different Plans used in the study are.

- Reservoir routing with PMF as lateral inflow and reservoir at FRL condition (811.68m).
- Reservoir routing with PMF as lateral inflow, with one additional spillway gate and reservoir at FRL condition.
- Reservoir routing with PMF as lateral inflow and reservoir at 810 m.
- Reservoir routing with PMF as lateral inflow and reservoir at 810.3 m.
- Reservoir routing with PMF as lateral inflow and reservoir at 810.4 m.
- Reservoir routing with PMF as lateral inflow and reservoir at 810.5 m.
- Reservoir routing with PMF as lateral inflow and reservoir at 810.6 m.

4 RESULTS AND DISCUSSION

4.1 Delineation of Catchment Area

TABLE 1

PHYSIOGRAPHIC PARAMETERS FROM BASIN PROCESSING

Sl No.	Parameter	Value	
1	Catchment area (A)	194	km2
2	Longest river length from outlet (L)	48.14	Km
3	Equivalent stream slope along longest stream (Seq.)	11.575	m/km

I. The catchment area and stream profile are generated from the ARC-GIS

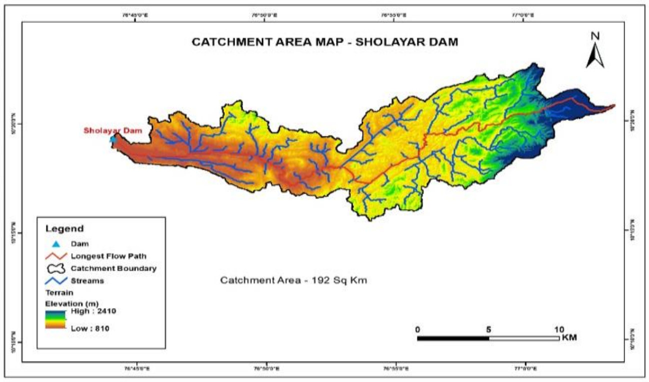

Fig. 1. Catchment area map

II. Determination of Equivalent stream slope

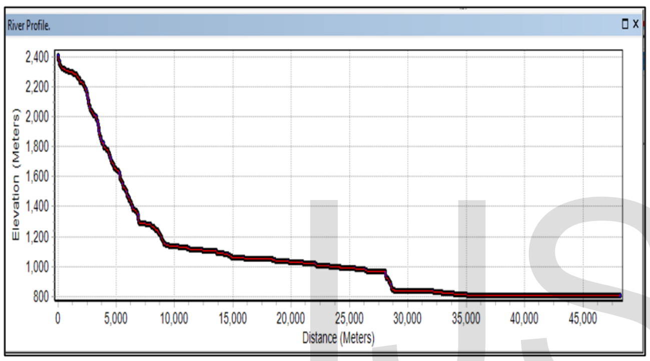

Fig. 2. Stream Profile

4.2 Synthetic Unit Hydrograph

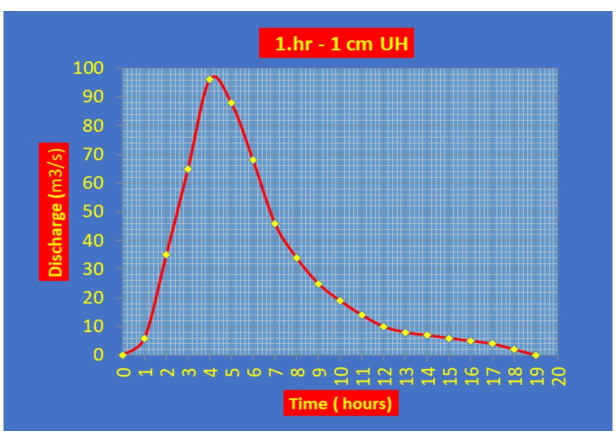

Fig. 3. Synthetic Unit Hydrograph, Unit hydrograph parameters are estimated using the equations given in flood estimation report.

4.3 Estimation of Design Storm

In the PMP Atlas, the nearest grid point to the catchment with higher one day rainfall value is WF 101-07 and PMP at that point s 524 mm. A design loss rate of 0.1 cm /hour.

TABLE 2
HOURLY DISTRIBUTION OF PMP

	Normalised Dist. Coefficient	Cumulative Rainfall depth		Incremental Rainfall depth		Loss rate	Effective Rainfall depth	
		Ist 12 hr. bell distribution	2nd12 hr. bell distribution	Ist 12 hr. bell	2nd12 hr. bell		Ist 12 hr. bell	2nd12 hr. bell
Hours		cm	cm	cm	cm	cm/hr	cm	cm
1	24	8.93	2.52	8.93	2.52	0.10	8.83	2.42
2	39	14.51	4.09	5.58	1.57	0.10	5.48	1.47
3	51	18.97	5.35	4.46	1.26	0.10	4.36	1.16
4	62	23.06	6.50	4.09	1.15	0.10	3.99	1.05
5	70	26.04	7.34	2.98	0.84	0.10	2.88	0.74
6	77	28.64	8.08	2.60	0.73	0.10	2.50	0.63
7	82	30.50	8.60	1.86	0.52	0.10	1.76	0.42
8	87	32.36	9.13	1.86	0.52	0.10	1.76	0.42
9	91	33.85	9.55	1.49	0.42	0.10	1.39	0.32
10	95	35.33	9.97	1.49	0.42	0.10	1.39	0.32
11	98	36.45	10.28	1.12	0.31	0.10	1.02	0.21
12	100	37.19	10.49	0.74	0.21	0.10	0.64	0.11
				37.19	10.49		35.99	9.29

TABLE 3
CRITICAL SEQUENCING OF RAINFALL

Time (hr)	UG Ordinate (cumecs)	Critical arrangement of rain fall increments		Critical 1 hr excessive rain fall after reversing the critical arrangement		Critical 1 hr excessive rain fall after reversing the critical arrangement
		Ist 12 hr. bell	2nd12 hr. bell	Ist 12 hr. bell	2nd12 hr. bell	
0.00	0.00					
1.00	6.00					0.64
2.00	35.00	2.5	0.21	0.64	0.11	1.02
3.00	65.00	3.99	1.05	1.02	0.32	1.39
4.00	96.29	8.83	2.42	1.39	0.32	1.39
5.00	88.00	5.48	1.47	1.39	0.42	1.76
6.00	68.00	4.36	1.16	1.76	0.42	1.76
7.00	46.00	2.88	0.74	1.76	0.63	2.88
8.00	34.00	1.76	0.63	2.88	0.74	4.36
9.00	25.00	1.76	0.42	4.36	1.16	5.48
10.00	19.00	1.39	0.42	5.48	1.47	8.83
11.00	14.00	1.39	0.32	8.83	2.42	3.99
12.00	10.00	1.02	0.32	3.99	1.05	2.50
13.00	8.00	0.64	0.11	2.50	0.21	0.11
14.00	7.00					0.32
15.00	6.00					0.32
16.00	5.00					0.42
17.00	4.00					0.42
18.00	2.00					0.63
19.00	0.00					0.74
						1.16
						1.47
						2.42
						1.05
						0.21

4.4 Inflow Hydrograph

Inflow hydrograph of Sholayar reservoir is derived for PMP. The rain fall corresponding to PMP 52.4 cm as per the PMP Atlas.The flood peak corresponding to PMP is 2303 m3/s.

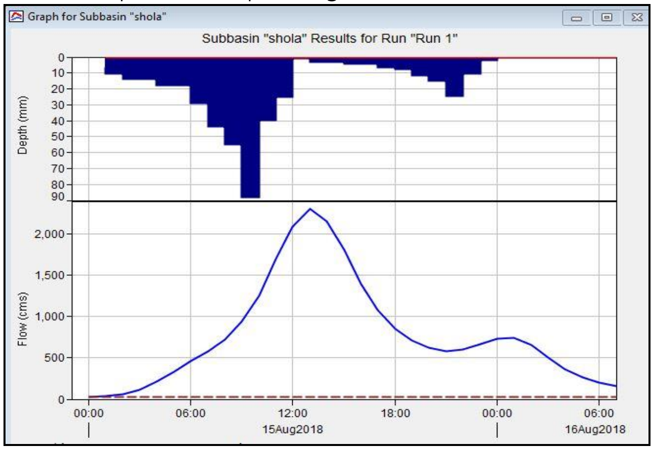

Fig. 4. Hydrograph for PMP

4.5 Reservoir Routing With PMF

PMF hydrograph is routed through reservoir at FRL condition to determine the maximum water level in the reservoir. The outflow hydrograph and stage hydrograph of the reservoir obtained is shown below. The maximum outflow is 1913 m3/s. The maximum water level in the reservoir is 812.23m.

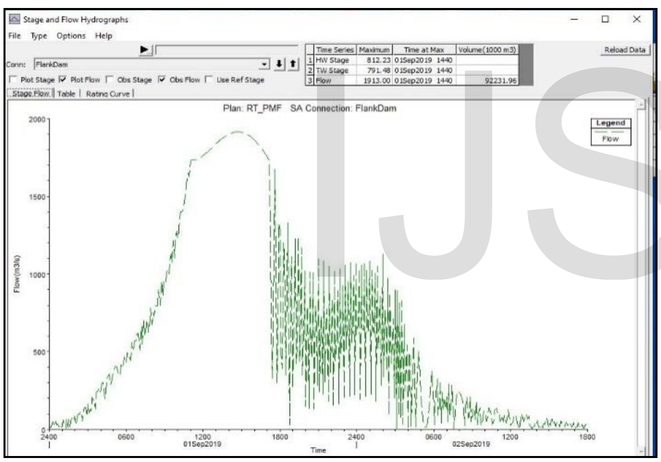

Fig. 5. Outflow Hydrgraph

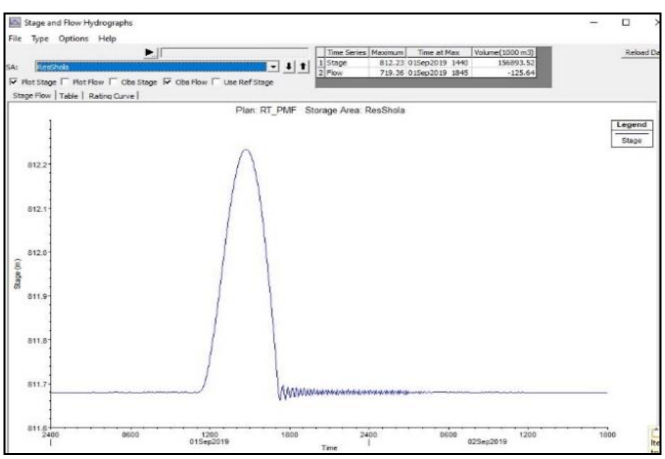

Fig. 6. Reservoir Stage Hydrograph

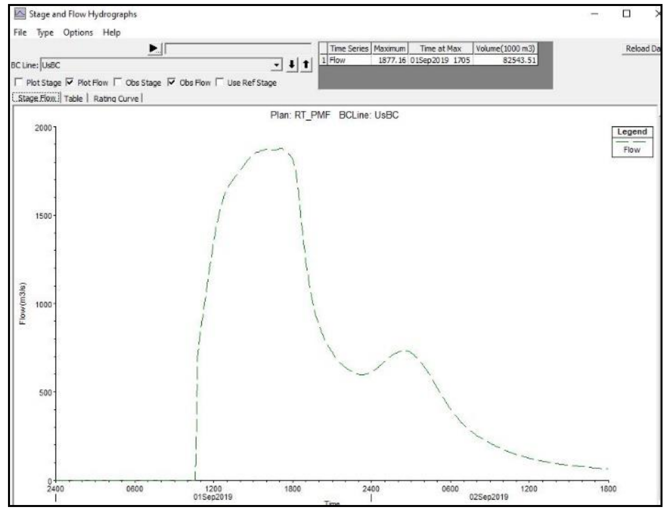

Fig. 7. Hydrograph at downstream boundary (at the rear end of the Poringalkuthu reservoir)

The peak of the hydrograph is attenuated from 1913 m3/s to 1877 m3/s. The travel time of flood wave from Sholayar to Poringalkuthu reservoir is 3hrs.

4.6 Check for Free Board

The top level of the dam is 812.60 m and Maximum Water Level obtained is 812.23m. Free board available is only 0.37m. To increase the free board to 1m, two options are considered. One is to study the possibility of adopting structural measures by providing additional gates and the other is adopting non-structural measures by lowering the operational level of the reservoir to a conservative level during active monsoon season.

4.6.1 Structural measures

Provision for one additional vent - Reservoir routing with PMF and reservoir at FRL & with provision for one additional gate.

Model was run with a provision for one additional vent of the same dimensions of the existing vents. It was found that water level in the reservoir after routing comes to 811.80. That is the free board availability is 0.80 m. Space restriction is there at site to provide a greater number of gates. More than that, the maximum release was also be increased to 2128 m3/s when one additional gate was added. This value is quite high due to large scale flooding in downstream.

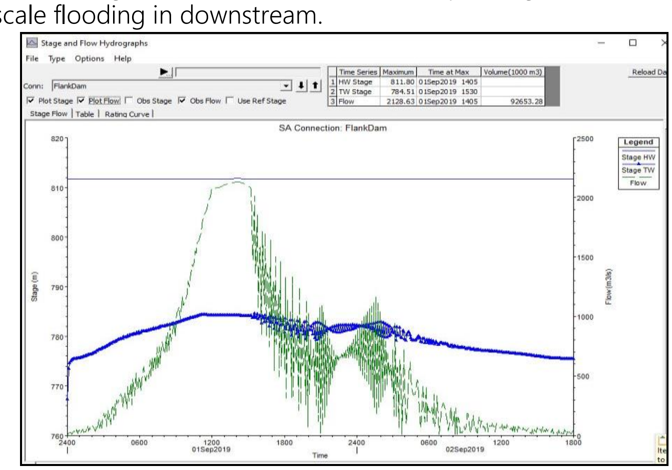

Fig. 8. Stage and Flood Hydrograph

4.6.2 Non-structural measures

Lowering the operational level in the reservoir - Reservoir routing with PMF for different water levels in the reservoir.

The PMF is routed through the reservoir with different reservoir levels. The model is run for the impingement levels 810, 810.3, 810.4, 810.5 & 810.60. The outputs are as shown below.

a) Trial -1: Routing PMF at 810 m.

Result:

Max water level - 811.32 m

Max Outflow -1577.78 m3/s

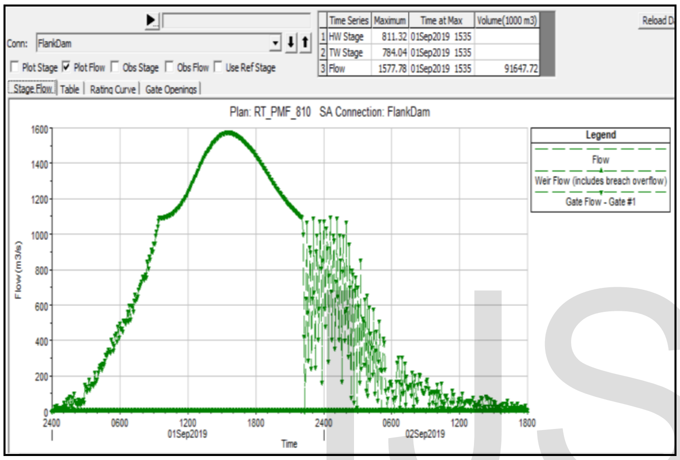

Fig. 9. Flow Hydrograph for Trial 1

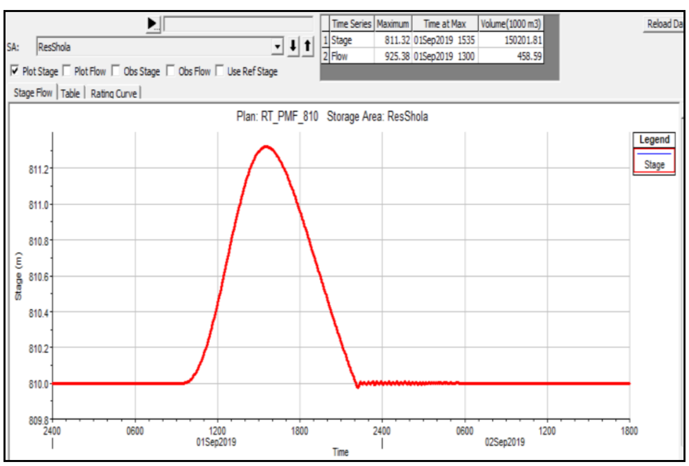

Fig. 10. Reservoir Stage Hydrograph for Trial 1

b) Trial -2: Routing PMF at 810.3

Result:

Max water level - 811.45 m

Max Outflow -1633.02 m3/s

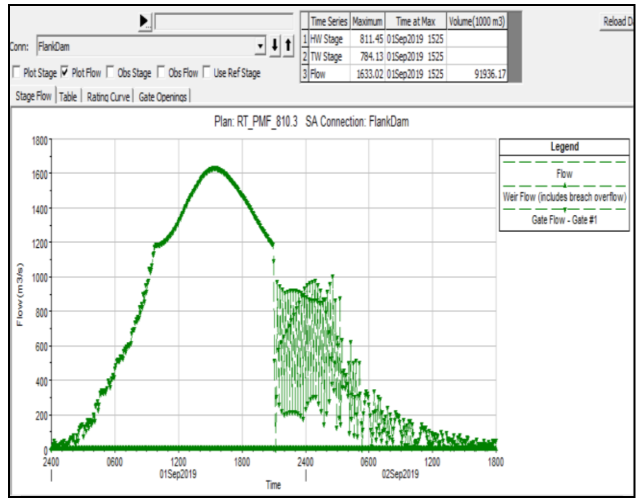

Fig. 11. Flow Hydrograph for Trial 2

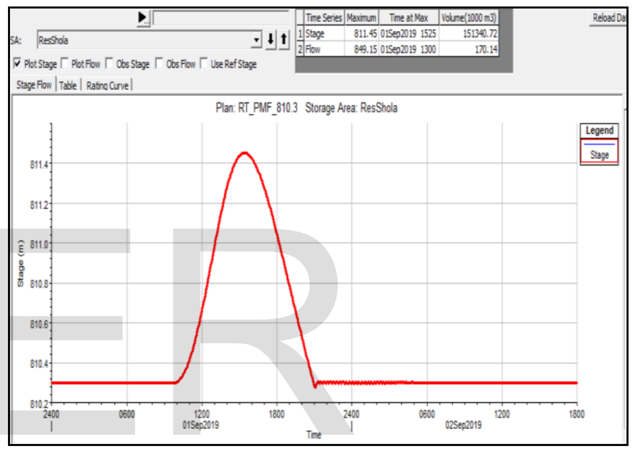

Fig. 12. Reservoir Stage Hydrograph for Trial 2

c) Trial -3: Routing PMF at 810.4

Result:

Max water level - 811.5 m

Max Outflow - 1651.78 m3/s

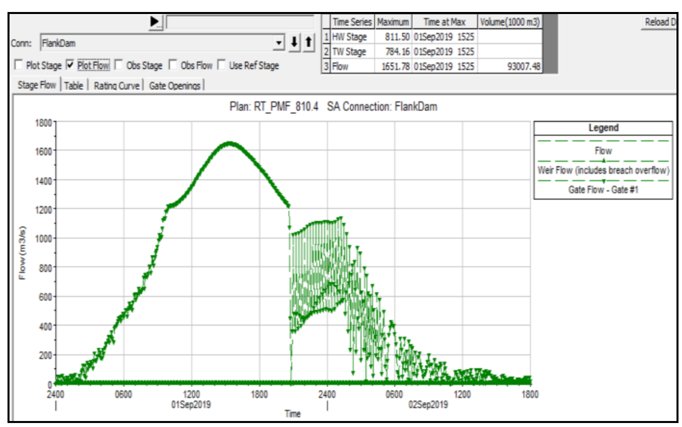

Fig. 13: Flow Hydrograph for Trial 3

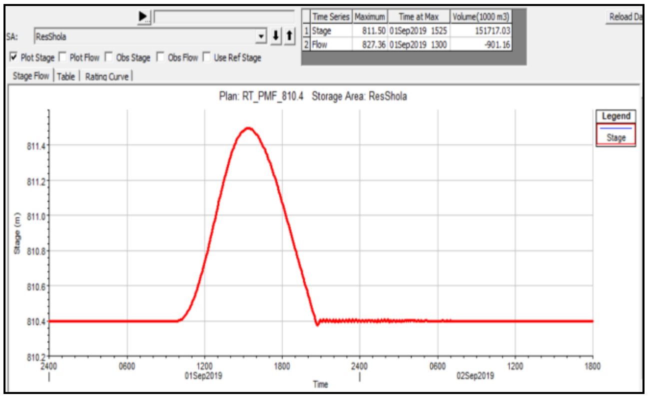

Fig. 14. Reservoir Stage Hydrograph for Trial 3

d) Trial -4: Routing PMF at 810.5

Result:
Max water level - 811.54 m
Max Outflow -1670.4 m3/s

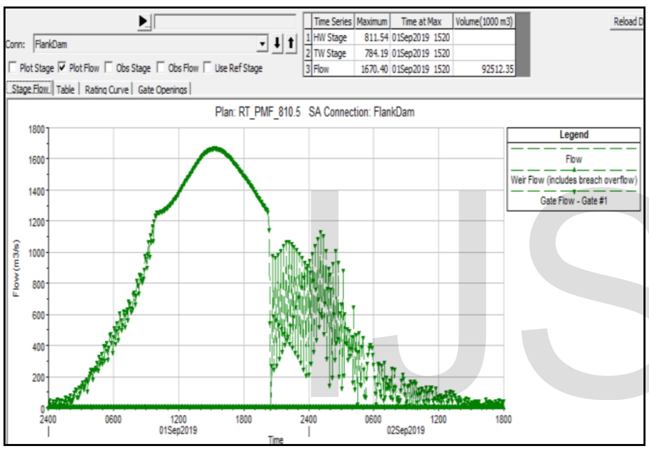

Fig. 15. Flow Hydrograph for Trial 4

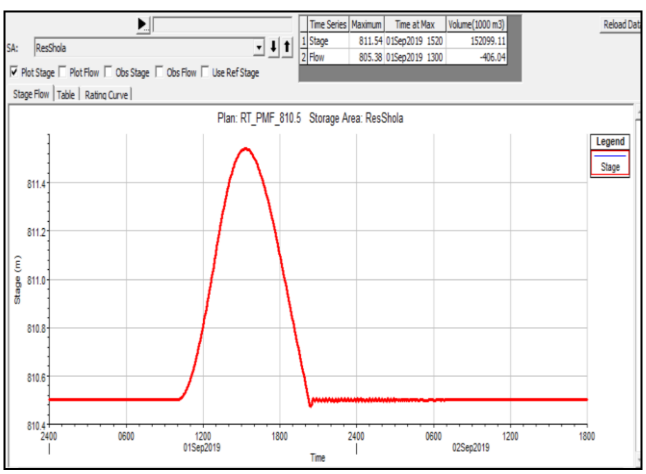

Fig. 16. Reservoir Stage Hydrograph for Trial 4

e) Trial -5: Routing PMF at 810.6

Result:
Max water level - 811.58 **m**
Max Outflow -1689.39m3/s

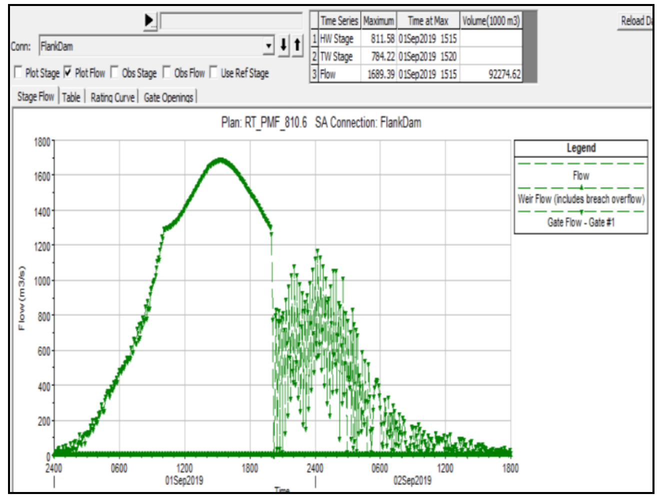

Fig. 17. Flow Hydrograph for Trial 5

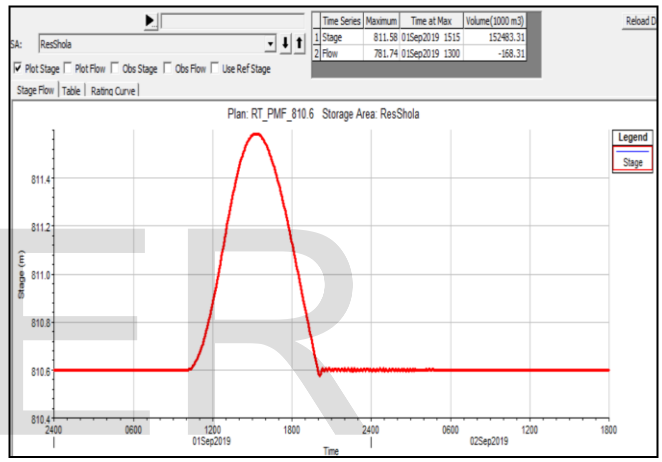

Fig. 18. Reservoir Stage Hydrograph for Trial 5

From the outpit of different trials, it is found that when the water level in the reservoir is 810.60, the maximum water level in the resevior after routing will become 811.60m with 1.0 m freeboard. Accordingly, the operating level of the reservoir shall be kept at 810.60 m during active monsoon season to have a flood cushion to ensure the hydrological safety of the dam.

5 CONCLUSIONS

5.1 General

The inflow design flood is now estimated as 2303 m3/s for a PMP value of 524mm against the original design flood of 1710 m3/s. Results of the present study is like the outcome of the study conducted by Central Water Commission to review the design flood of selected dams. Hence it is concluded that revised design flood of 2303 m3/s estimated based on the updated information and guidelines can be adopted as the design flood of Sholayar. The revised design flood has exceeded the original design flood by 34%. When the PMF is routed through the reservoir at FRL condition, the water level in the reservoir rises to 812.23m. The free board available is only 0.37m.

It is also attempted to find a suitable methodology to handle the increased design flood as part of the study. It is tried to keep the maximum water level in the reservoir 1m below the top level of dam, i.e., 811.60m. Two alternative approaches are considered. Option 1- is a structural measure by providing additional vents to pass excess discharge. Option -2 is a non-structural measure by re fixing the maximum water level in the reservoir to handle the PMF without encroaching the water level in the reservoir above 811. 60m.

For Option 1, model is run with PMF at FRL condition, i.e., 811.68m with one more vent of size 10.97m X 6.40m. From the model output, it can be concluded that this Option is not acceptable as the maximum water level in the reservoir rises to 811.80 and maximum discharge to 2128m3/s. From the above it found that the free board available is less than 1.0m. Downstream discharge is also increased considerably which may have adverse impact on the downstream plains.

In the Option-2, it is found that by keeping the reservoir level at 810.60m, the PMF can be moderated from 2303 m3/s to 1689m3/s with maximum water level in the reservoir 811.60. It is therefore concluded that in active monsoon season, the water level in the reservoir may be kept as 810.60m against 811.68m.

When water level is to be maintained as 810.60m, it may be required to release the water from the reservoir i.e., before water level in the reservoir reaches the present FRL. This will in turn cause loss in power generation which is the primary objective of the project. To avoid the generation loss consequent to the early releases, it is proposed to install an inflow forecasting system in the basin and to release water based on the real time inflow series with a flexibility of varying the reservoir level between 810.60m & 811.60m. It is also suggested to introduce an integrated reservoir operation system considering the upstream reservoir.

5.2 Future Works

There is scope for future studies on installing an inflow forecast system in the basin works with inputs from robust weather prediction model and development of an integrated reservoir operation protocol to optimise the utilisation of available water resources with the help of a real time hydrologic/hydraulic model. Flood modelling may be carried out using high precision terrain data to obtain more precise inundation maps.

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