# STORM ANALYSIS AND QUASI DISTRIBUTED HYDROLOGIGAL MODELLING FOR DESIGN FLOOD REVIEW OF UKAI DAM, GUJARAT

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## ABSTRACT

*The Ukai multipurpose project forms the terminal reservoir across River Tapi at village Ukai harnessing nearly half of the river flow for benefits of irrigation, hydropower and other facilities. The catchment area up to the dam site is 62037 sq.km out of which about 83% lies in the State of Maharashtra, 15.5% in MP and 1.5% in Gujarat. Ukai dam is a composite earthen and masonry dam with a maximum height of about 80.7 m above its deepest foundation and a gross storage capacity of 7414 MCM. As per IS: 11223, the dam qualifies for PMF as its inflow design flood for spillway capacity and hydrologic safety. The flood estimation in such cases is done using hydro-meteorological approach by subdividing the catchment area into smaller sub-catchments to ensure applicability of principles of proportionality and superimposibility . Accordingly, the Ukai catchment has been subdivided into 20 sub-catchments.. Since the base of the unit hydrograph extends for more than 52 hours for most of the sub-catchments and the entire catchment as whole, a three day storm dated 04-06 August 1968 with eye at Golkund and having a recorded three day depth of 977 mm at storm centre has been selected for the storm analysis. The corresponding 2day and 1day storm considered are, the storm dated 05-06 Aug 1968 and 06 Aug 1968 having storm centres at Ukai dam site and Jawhar respectively. While transposition of 1day, 2day and 3day storm isohyets for maximization, it was found that the storm centers of 1day, 2day and 3day storms were coming very close to each other making the storm almost stationary. This was not creating the natural storm movement pattern and was also resulting in an anomaly by giving lesser 3 day storm depth than 2 day storm depth in a number of sub-catchments. To protect the natural pattern of storm movement , analysis has been carried out by bodily moving the storm centers of 1 day and 2 day patterns in consonance with the movement of 3 day storm center at location for obtaining maximized transposed depth. With the above storm movement, Depth-Duration (DD) depths of 1day, 2day and 3day storms for the entire catchment have been computed and 3day storm transposed maximized depth distributed in ratio of 1day DD depth to 3day DD depth and 2day DD depth to 3day DD depth of each sub-catchment to get 1day, 2day and 3 day storm depths maintaining the natural pattern. In the present paper, the need for preserving the storm movement pattern while transposition is thus highlighted. The 12 hour bell distribution for the 6 bells has been carried out using the time distribution coefficient from the PMP Atlas for Narmada, Tapi and Other adjoining river basins. Using the Clark UH a quasi distributed model was set up in HEC-HMS to get the design flood for Ukai dam. The present paper describes the methodology adopted for the design flood computation including the storm analysis.*

***Keywords*** *- Storm transposition; Depth-Duration (DD) analysis; Quasi distributed hydrological modelling*

## 1. INTRODUCTION

The Ukai dam (Latitude 210 14'52''N, Longitudes 730 35'24''E) is a composite earthen and masonry dam with a maximum height of 80.77 m above its deepest foundation. The total length of the dam is 4927 m of which, 4058 m is earth dam of zoned fill type. Masonry gravity dam, including the 425.20 m long spillway and the power dam, left/right transitions over the remaining length. The spillway, located on the left bank of the river, is provided with 22 radial crest gates of 15.55 m x 14.78 m size. The maximum discharging capacity of the spillway at MWL is 46270 cumec. The corresponding capacity at FRL is 37860 cumec. All the radial gates are operated by electric motors supplemented with manual operation. The reservoir upto its FRL of 105.16 m, has a live storage capacity of 7369 MCM with a water spread of about 600 Sq.km and maximum length of about 112 Km. The reservoir is expected to attain a maximum level of MWL 106.99 m while passing the Probable Maximum Flood (PMF) of 59920 cumec. As per BIS criteria the Ukai dam qualifies for Probable Maximum Flood (PMF) as its design flood.

## 2. PHYSIOGRAPHIC PARAMETERS

The physiographic parameters of Tapi river catchment at Ukai dam site have been estimated by GIS processing of SRTM DEM. The catchment area plan with adopted sub-catchments is shown in Fig.1.

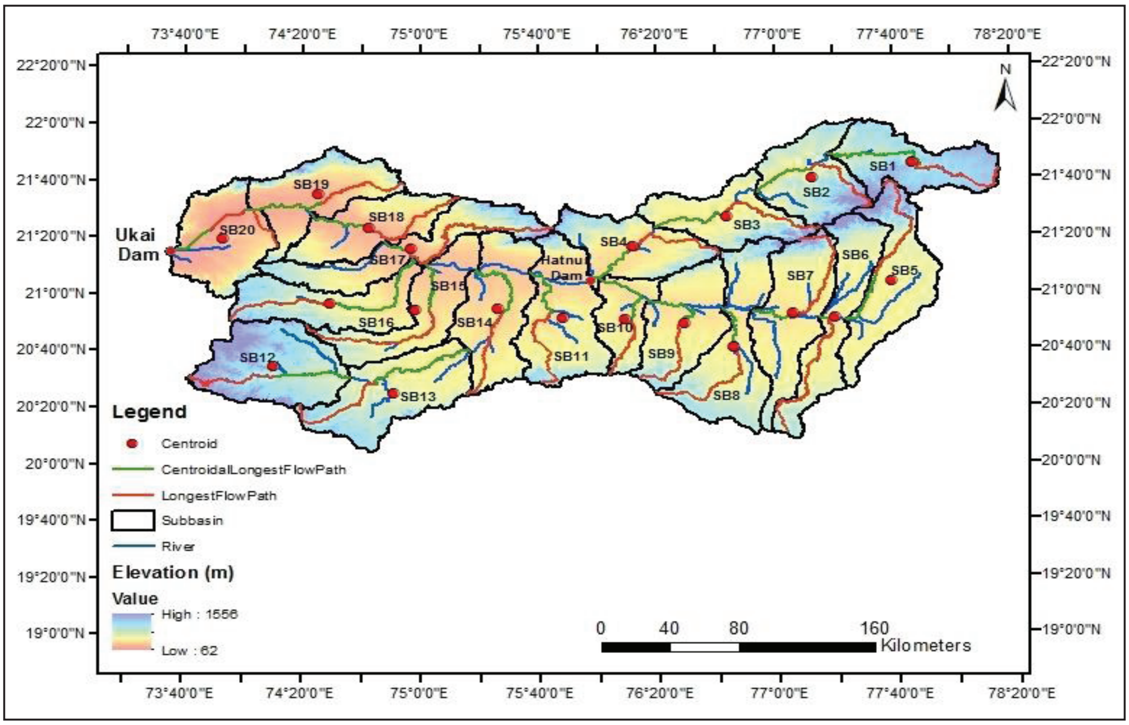


**Fig. 1** : Catchment area plan of Tapi river at Ukai dam site

As per GIS mapping the catchment area of Ukai dam sites is about 62037sq.km. Since the catchment area at above dam site is much larger for developing a unit hydrograph for the entire catchment, hence, the same has been divided into twenty sub-catchments to get the catchment area of each sub catchment less than 5000 sq.km. In such cases design flood computations require a quasi distributed hydrological model set up, consisting of sub-catchments of smaller size where the lumped output of each sub catchment is received at the sub catchment outlet and then channel routed through the river reach to get its net contribution at the project site. The sub-catchments parameters viz. catchment area of each sub catchment, longest flow path, centroidal longest flow path, equivalent stream slope of each sub-catchment as obtained from GIS processing are given in Table 1.

**Table 1** : Physiographic parameters of the sub-catchments

| S.No. | Sub-catchment | Total Area | Longest flow path L | Centroidal longest flow path Lc | Equivalent Stream Slope |
|---|---|---|---|---|---|
| | | sq.km | km | km | m/km |
| 1 | SB1 | 2877 | 168.4 | 78.0 | 2.00 |
| 2 | SB2 | 2841 | 125.2 | 40.6 | 3.14 |
| 3 | SB3 | 2687 | 137.5 | 52.0 | 2.00 |
| 4 | SB4 | 2760 | 121.9 | 43.7 | 1.57 |
| 5 | SB5 | 3410 | 165.2 | 51.5 | 2.00 |
| 6 | SB6 | 3110 | 140.5 | 8.5 | 1.37 |
| 7 | SB7 | 3540 | 137.1 | 36.4 | 1.87 |
| 8 | SB8 | 3772 | 145.6 | 40.4 | 1.75 |
| 9 | SB9 | 3054 | 129.8 | 53.0 | 1.69 |
| 10 | SB10 | 1633 | 106.3 | 55.8 | 1.31 |
| 11 | SB11 | 3659 | 133.1 | 48.5 | 2.06 |
| 12 | SB12 | 3795 | 131.3 | 43.4 | 2.84 |
| 13 | SB13 | 3727 | 164.4 | 84.3 | 1.94 |
| 14 | SB14 | 3495 | 143.5 | 69.1 | 1.33 |
| 15 | SB15 | 2873 | 153.8 | 41.0 | 2.42 |
| 16 | SB16 | 2960 | 161.5 | 86.3 | 2.65 |
| 17 | SB17 | 3110 | 157.8 | 17.9 | 2.27 |
| 18 | SB18 | 2642 | 128.3 | 42.8 | 1.24 |
| 19 | SB19 | 3031 | 121.3 | 53.7 | 1.54 |
| 20 | SB20 | 3061 | 97 | 30.2 | 1.08 |

## 3. UNIT HYDROGRAPH FOR SUB CATCHMENTS

The unit hydrographs for the sub-catchments have been developed using Clark method of HEC-HMS. The Clark unit hydrograph parameters viz time of concentration and storage coefficient as adopted for different sub-catchments are given in Table 2.

**Table 2** : Clark unit hydrograph parameters for different sub-catchments

| Sub-catchment | Tc | K |
|---|---|---|
| | (hr) | (hr) |
| SB1 | 35 | 7.20 |
| SB2 | 18.7 | 4.40 |
| SB3 | 20 | 4.40 |
| SB4 | 19.8 | 4.40 |
| SB5 | 30.8 | 6.50 |
| SB6 | 32 | 8.80 |
| SB7 | 20.8 | 4.80 |
| SB8 | 29.7 | 6.80 |
| SB9 | 25.4 | 5.60 |
| SB10 | 19.7 | 4.40 |
| SB11 | 23.4 | 6.20 |
| SB12 | 23.8 | 6.40 |
| SB13 | 30.2 | 6.80 |
| SB14 | 24.4 | 5.60 |
| SB15 | 27.4 | 7.40 |
| SB16 | 23.1 | 5.40 |
| SB17 | 25.4 | 7.80 |
| SB18 | 23.4 | 6.00 |
| SB19 | 22.3 | 5.20 |
| SB20 | 21.8 | 6.20 |

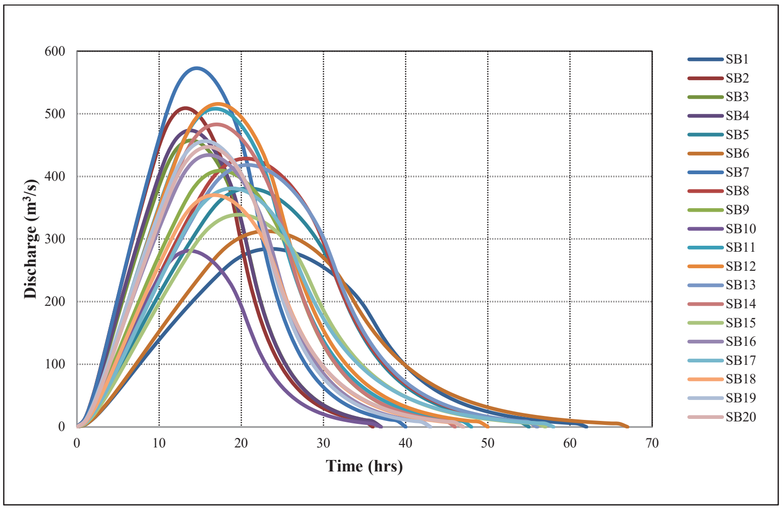


**Fig. 2** : Plot of unit hydrographs of different sub-catchments

## 4. DESIGN STORM STUDIES

According to WMO: 332, 1986, Section 1.3.2 due care need to be exercised in transposing storms to catchment larger than 50,000 sq.km as it may result in unreasonably excessive PMP estimation since deposits of heavy rainfall at rates computed from maximum moisture influx as released throughout thousands of sq.km by rapidly developed storms mechanisms of maximum efficiency continuously for 3 to 5 days may result in unrealistically severe situation of flooding that is not experienced by the catchment. Therefore, for the purpose of obtaining reliable levels of PMP depths over the sub-catchments, the influencing factors of storm centering and re-orientation need to be decided carefully and confirmed to reasonable level.

Ukai Dam lies in Tapi Basin. The Catchment lies in two PMP Grids mainly 103-U and 103-L of the Narmada and Tapi Basin PMP Atlas prepared jointly by CWC and IMD in year 2015. As per PMP Atlas the 1day storm of 6th Aug 1968 with recorded peak depth as 445 mm having eye at Ukai dam site, 2 day storm of 05-06August 1968 with recorded peak depth as 752 mm having eye at Jawhar and 3 day storm of 04-06Aug 1968 with recorded peak depth as 977 mm having eye at Golkund are the most critical storms for design storm analysis of Ukai catchment.

For the present study, the catchment area of Ukai dam site has been sub-divided into 20 sub-catchments in order to have catchment area of each sub-catchment less than 5000 sq.km. For computation of design depths realized in different sub-catchments, first the three day storm isohyets have been critically transposed to get the maximized depth for the entire catchment of 62037 sq.km. To get the one day and two storm depths of each sub-catchment the storm isohyets of one day and two day storms have been bodily moved in the same pattern as that of 3day storm. The storm centers of 1 day 2day and 3 day storms and their transposed locations are shown in Fig.3. The isohyets of 1day and 2day storms after bodily movement are shown in Fig.4 and 5 respectively. The transposed isohyets of 3day storm for maximized depth of entire catchment is presented in Fig.6.

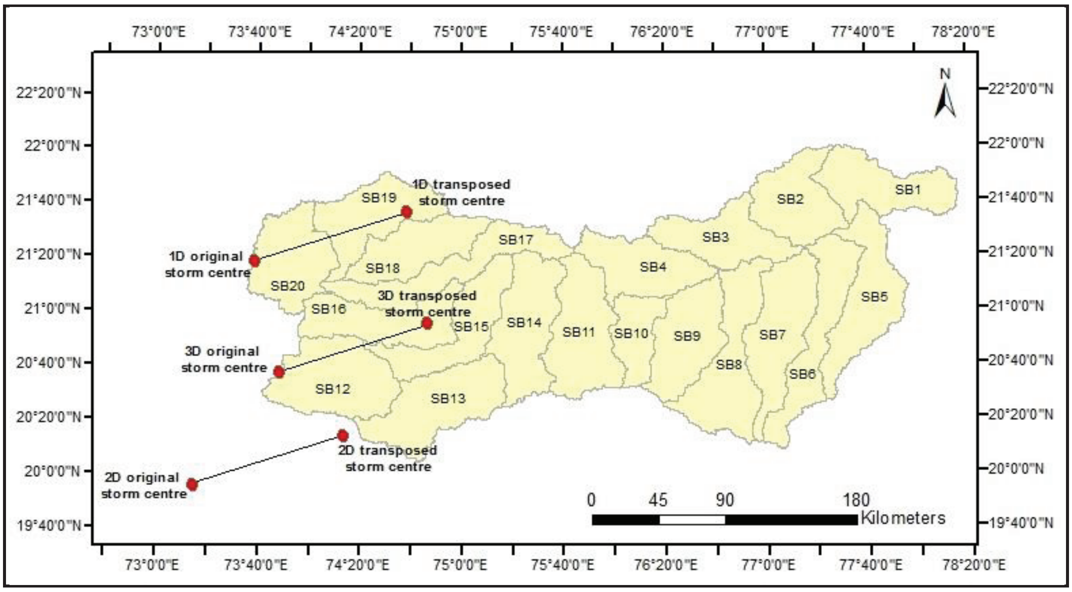


**Fig. 3** : Original and transposed locations of 1Day, 2Day and 3Day storm centres

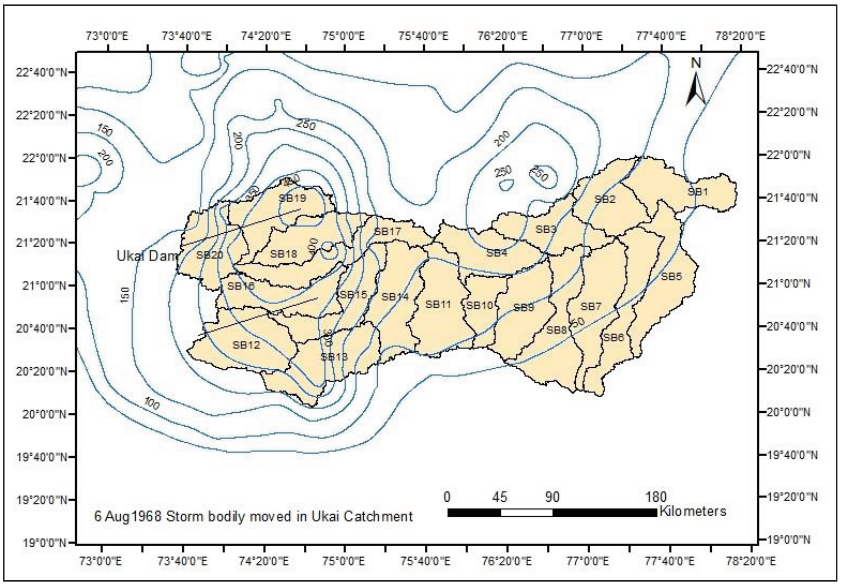


**Fig. 4** : 6 August 1968 storm bodily moved over Ukai catchment

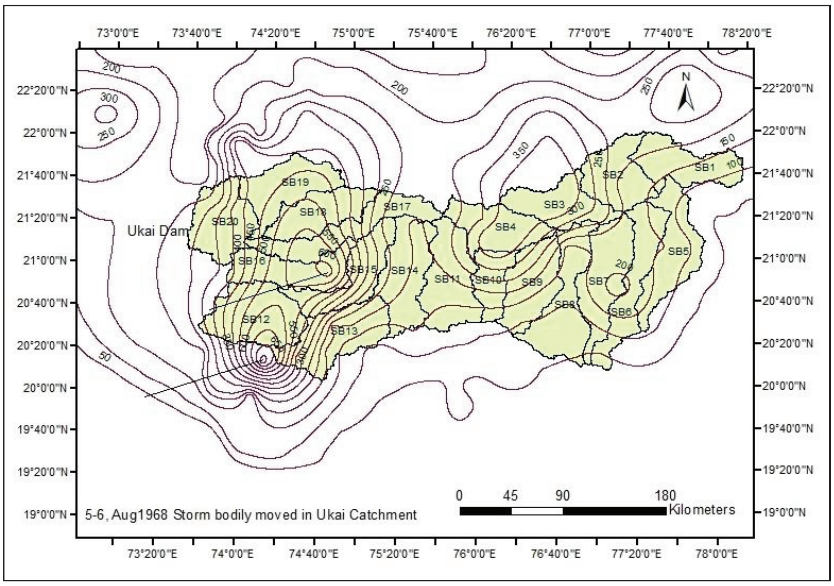


**Fig. 5** : 5-6 August 1968 storm bodily moved over Ukai catchment

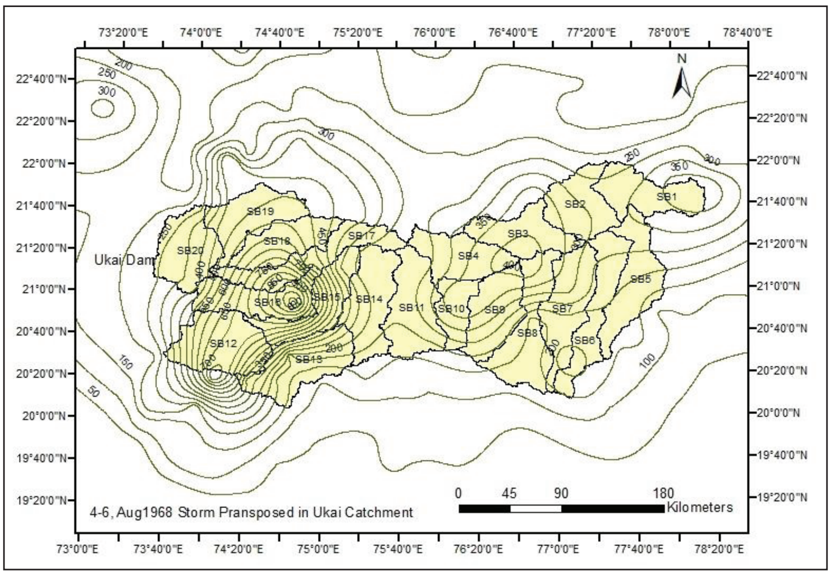


**Fig. 6** : 4-6 August 1968 storm transposed at Ukai catchment for maximized depth

For the above bodily moved position, the realized depths for entire catchment of 62037 sq.km have been computed for 1day and 2 day storms. The computed overall three day, two day and one day storm depths in the drainage area of the Dam are 357.4 mm, 284.3mm and 179.2 mm respectively. The 1 day storm depth for each sub-catchment has been computed using the formula, 1 day depth for sub-catchment = (1day depth for entire catchment/3day depth for entire catchment) x (3day depth of the sub-catchment). Similarly the 2 day storm depth for each sub-catchment has been computed using the formula, 2 day depth for sub-catchment = (2day depth for entire catchment/3day depth for entire catchment) x (3day depth of the sub-catchment). The bodily moved transposition depths have been compared with the Depth-Duration (DD) depths. The computed overall three day, two day and one day DD depths in the drainage area of the dam were 247.1 mm, 207.7 mm and 129.6 mm respectively. On comparison of both, the bodily moved transposition depths have been found to be more representative and critical for estimation of PMP for the project catchment. Further, the ratio of 1 day to 3 day and 2 day to 3 day for bodily moved transposition for the entire catchment is 50% and 80% respectively, while the same with respect to DD analysis is 52% and 84% respectively. Thus, the above comparison establishes that the bodily moved transposition also captured the 1day and 2 day storm depths pattern which had physically occurred.

The realized storm depths for different sub-catchments have been multiplied with Transposition Adjustment Factor (TAF) of 0.85 and Moisture Maximization Factor (MMF) of 1.42 to get the PMP depths for each sub-catchment. The computed Transposed depths and PMP depths for each sub-catchment is shown in Table-3, which have been adopted for design flood computations of Ukai dam.

**Table 3** : Design Storm depths for catchment of Ukai dam

| Sub catchment | Catchment Area (km$^2$) | 1 day,2 day and 3 day storm depths | | | | | |
|---|---|---|---|---|---|---|---|
| | | Realized depths (mm) | | | PMP (mm) | | |
| | | 1-day | 2-day | 3-day | 1-day | 2-day | 3-day |
| SB1 | 2877 | 152.7 | 242.3 | 304.6 | 184.3 | 292.4 | 367.6 |
| SB2 | 2841 | 154.1 | 244.5 | 307.3 | 186.0 | 295.1 | 370.9 |
| SB3 | 2687 | 186.1 | 295.3 | 371.2 | 224.6 | 356.4 | 448.0 |
| SB4 | 2760 | 162.2 | 257.3 | 323.4 | 195.7 | 310.5 | 390.4 |
| SB5 | 3410 | 108.0 | 171.3 | 215.4 | 130.3 | 206.8 | 260.0 |
| SB6 | 3110 | 105.0 | 166.6 | 209.4 | 126.7 | 201.1 | 252.7 |
| SB7 | 3540 | 122.4 | 194.3 | 244.2 | 147.8 | 234.5 | 294.7 |
| SB8 | 3772 | 119.5 | 189.6 | 238.4 | 144.2 | 228.9 | 287.7 |
| SB9 | 3054 | 142.4 | 225.9 | 283.9 | 171.8 | 272.6 | 342.7 |
| SB10 | 1633 | 158.1 | 250.8 | 315.3 | 190.8 | 302.7 | 380.5 |
| SB11 | 3659 | 117.7 | 186.7 | 234.7 | 142.1 | 225.4 | 283.3 |
| SB12 | 3795 | 275.1 | 436.4 | 548.6 | 332.0 | 526.7 | 662.2 |
| SB13 | 3727 | 148.7 | 235.9 | 296.6 | 179.5 | 284.8 | 358.0 |
| SB14 | 3495 | 137.8 | 218.6 | 274.8 | 166.3 | 263.8 | 331.7 |
| SB15 | 2873 | 260.3 | 413.0 | 519.2 | 314.2 | 498.5 | 626.7 |
| SB16 | 2960 | 349.7 | 554.8 | 697.5 | 422.1 | 669.7 | 841.8 |
| SB17 | 3110 | 277.7 | 440.6 | 553.9 | 335.2 | 531.8 | 668.5 |
| SB18 | 2642 | 271.1 | 430.1 | 540.7 | 327.2 | 519.2 | 652.7 |
| SB19 | 3031 | 218.9 | 347.3 | 436.6 | 264.2 | 419.2 | 527.0 |
| SB20 | 3061 | 157.8 | 250.3 | 314.7 | 190.4 | 302.1 | 379.8 |

## 5. TIME DISTRIBUTION OF RAINFALL

The time distribution of rainfall has been taken from the PMP Atlas of Narmada and Tapi basin river prepared by CWC in January, 2015. The sub-catchments SB1-SB10 lies in Grid 103-U and sub-catchments SB11-SB20 lies in Grid 103-L. As 3 day PMP has been used for estimating the design flood, the incremental daily PMP for each sub catchment has been worked out as follows:

3rd day PMP = (3 day PMP) - (2 day PMP)

2nd day PMP = (2 day PMP) - (1 day PMP)

The 1st day, 2nd day and 3rd day PMP along with PMP depths for each bell has been computed. The TD coefficients used for bell distributions are given in Table 8.

Further, the design flood computations have been carried out by adopting the bells of 12 hour each, taking the 75% rainfall depth contribution in 1st 12 hour bell and 25% rainfall depth contribution in 2nd 12 hour bell for the rainfall of each day, for the sub-catchments SB1 to SB10, as per distribution coefficient of Grid 103-U. For sub-catchments SB11 to SB20, the PMP depth for 1st 12 hour bell has been taken as 68.5% and for 2nd 12 hour bell has been taken as 31.5% of the rainfall of each day of the above sub-catchments as per distribution coefficient of Grid 103-L. For 3 days rainfall the considering the 2 bells for each day total 6 bells with sequence B1B2B3B4B5B6 have been prepared. The hourly distribution of bell rainfall has been carried out taking the normalized distribution coefficients as in Table 4.

**Table 4** : Normalized distribution coefficient for 12 hour bell

| Time (hr) | Normalized Distribution coefficient for 12 hr bell (%) for SB1 to SB10 | Normalized Distribution coefficient for 12 hr bell (%) for SB11 to SB20 |
|---|---|---|
| 1 | 26.53 | 22.92 |
| 2 | 41.47 | 40.15 |
| 3 | 52.13 | 49.93 |
| 4 | 60.67 | 55.77 |
| 5 | 68.00 | 61.02 |
| 6 | 75.47 | 65.99 |
| 7 | 81.47 | 72.12 |
| 8 | 85.47 | 78.39 |
| 9 | 91.07 | 83.36 |
| 10 | 94.53 | 89.64 |
| 11 | 97.73 | 94.16 |
| 12 | 100.00 | 100.00 |

## 6. LOSS RATE AND BASE FLOW

A design loss rate of 0.1 cm /hour as per CWC FER 3(b) of upper Narmada and Tapi sub zone for SB1 to SB10 and 0.5 cm /hour as per FER 3(c) of lower Narmada and Tapi sub for SB11 to SB20 has been adopted for design flood computation. Further, the base flow has been adopted as 0.05 $m^3/s/sq.km$.

## 7. HOURLY DISTRIBUTION AND CRITICAL SEQUENCING OF RAINFALL

The hourly distribution of rainfall of each bell has been carried out taking the normalized distribution coefficients of Table-4. In order to keep the rainfall sequence in proper order, the critical sequencing of hourly effective rainfall of the bells of the sub-catchments SB1 to SB10 has been carried out with respect to UH of sub-catchment SB7. The critical sequencing of hourly effective rainfall of the bells of the sub-catchments SB11 to SB20 has been carried out with respect to UH of sub-catchment SB16.

## 8. DESIGN FLOOD COMPUTATION

The convolution and channel routing of flood hydrographs of different sub-catchments have been carried out on HEC-HMS hydrological model. The HEC-HMS model set up is presented in Fig.7. The reversed critical sequence of hourly effective rainfall with bell sequence B3B4B1B2B5B6 have been convoluted with UH of that sub-catchment. The base flow contributions of the sub-catchments have been added to get the total response function viz flood hydrograph at the outlet of that sub-catchment. Further, as shown in Annexure-1 flood hydrograph of SB1 sub-catchment coming at outlet (Jn1) has been channel routed through river reach R1 to get its response function at Jn2. Similarly the flood hydrograph of SB2 and routed flood of reach R1 received at Jn2 has been channel routed through reach R2. Similarly

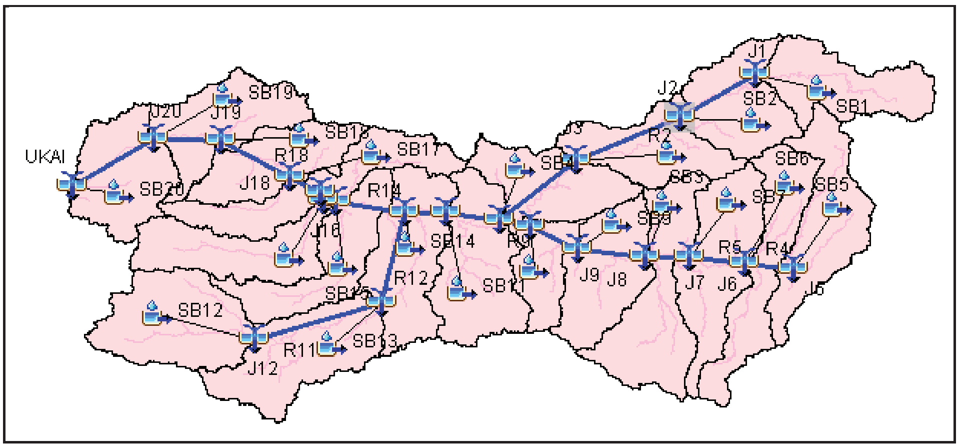


**Fig. 7** : HEC-HMS model set up for PMF computation of Ukai dam

lumped response of other sub-catchments and routed response through the reaches received at different junction have been channel routed till Junction J20.The combined outflow from Jn20 has been channel routed through reach R20 and added with the lumped response of SB20 to get the design flood (PMF) at junction Ukai.

The channel routings through the river reaches as per the model set up have been carried out using Muskingum method. For stability of Muskingum routing algorithm $\Delta t > 2KX$, hence channel routing in river reaches have been carried out steps by dividing the routing reach into twenty sub reaches(R1-R20).The backwater effected reaches are also analyzed separately for the k values. The Muskingum K and X parameters used for the different routing reaches are given in Table 5.

**Table 5** : Muskingum routing parameters

| Reach | Length | Muskingum 'K' | Muskingum 'X' | Sub reaches |
|---|---|---|---|---|
| | km | hr | | |
| R1 | 60.3 | 7.5 | 0.2 | 4 |
| R2 | 84.5 | 10.6 | 0.2 | 5 |
| R3 | 66.7 | 10.3 | 0.18 | 4 |
| R4 | 20.6 | 2.6 | 0.2 | 2 |
| R5 | 57.2 | 7.2 | 0.2 | 3 |
| R6 | 24.7 | 3.1 | 0.2 | 2 |
| R7 | 55 | 6.9 | 0.2 | 3 |
| R8 | 36 | 6.0 | 0.15 | 2 |
| R9 | 8.4 | 1.4 | 0.15 | 1 |
| R10 | 40.2 | 5.0 | 0.2 | 3 |
| R11 | 100.3 | 14.4 | 0.2 | 6 |
| R12 | 107.2 | 13.4 | 0.2 | 6 |
| R13 | 37.3 | 4.7 | 0.2 | 2 |
| R14 | 35.8 | 4.0 | 0.2 | 2 |
| R15 | 10.9 | 1.8 | 0.15 | 1 |
| R16 | 3.2 | 0.4 | 0.2 | 1 |
| R17 | 22.5 | 3.8 | 0.15 | 2 |
| R18 | 59.6 | 9.9 | 0.15 | 4 |
| R19 | 44.9 | 6.9 | 0.18 | 3 |
| R20 | 53.4 | 8.9 | 0.15 | 3 |

## 9. PROBABLE MAXIMUM FLOOD (PMF) FOR KADANA DAM

Based on the methodology discussed above, the estimated Probable Maximum Flood (PMF) for Ukai dam is 59470 $m^3/s$. The PMF hydrograph plot is given in Fig.8. The estimated design flood lies between average envelope curve of 43327 $m^3/s$ and upper envelope of 75415 $m^3/s$.

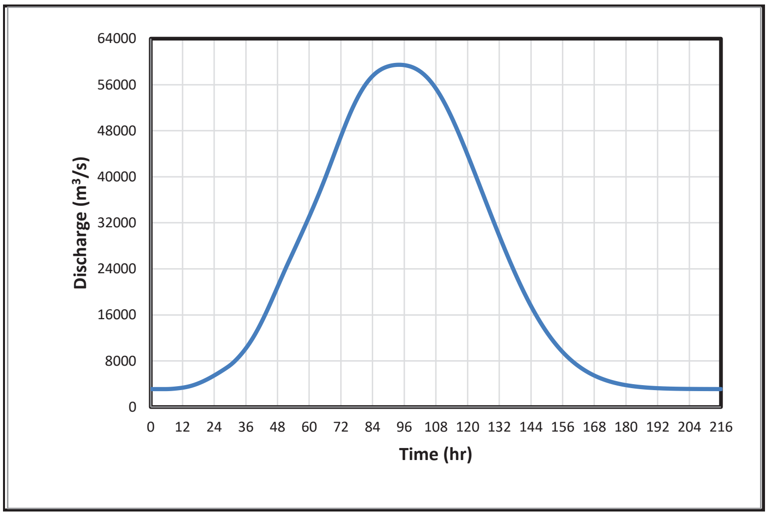


**Fig. 8** : PMF hydrograph for Ukai dam

## 10. CONCLUSION

In the case of Ukai dam the drainage area of Tapi river at dam site is about 62000 sq.km and for estimating the PMP depths for such a large are due care is necessary to have proper estimate of PMP for each sub-catchment. For the present case the PMP estimate for each sub-catchment has been decided considering the storm transposition of 3 day storm and bodily movement of 1 day and 2 day storms. The computed values have also compared with the value obtained from Depth Duration DD analysis and rainfall patterns in different sub-catchments with adjustment in proportion of 3 day DD and 3 day Transposed depths.. Therefore, for design flood computations for such a large catchment it is desirable that in order to obtain a reliable levels of PMP depths over the sub-catchments, the influencing factors of storm centering and re-orientation need to be decided carefully and confirmed to reasonable level.

### Disclaimer

The views expressed in the paper are purely personal and are not necessarily the views of the organisation.

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