Dam Break Analysis using HECRAS with DEM Generated Geometry

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Abstract— Dams are considered as structures containing dangerous forces. Even though the dam failures are comparatively rare, they can cause immense damage and loss of life and properties when they occur. This study deals with the dam break analysis of a gravity dam using HEC-RAS with the river geometry derived from SRTM Digital elevation model. The preparation of inundation map is done using HECGeoRAS. For the analysis, maximum probable flood was determined using GIUH based Clark's method. The area of inundation for probable maximum flood, time travel etc., were computed by conducting the dam break analysis.

Keywords—PMP; IUH; flood; GIUH; PMF

I. INTRODUCTION

Dams are considered as "installations containing dangerous forces". Dam failures are comparatively rare, but can cause immense damage and loss of life and properties when they occur. Dam break may be summarized as the partial or catastrophic failure of a dam which results in quick release of water from the reservoir. In the event of dam break, the energy stored behind the dam is capable of causing rapid and unexpected flooding on the downstream, resulting in loss of life and damages caused to properties. Analysis of dam failures helps in providing adequate warnings to the public. So dam break analysis and preparation of inundation map is very important.

The purpose of the dam break analysis has been to illustrate how the flood wave propagates and attenuates along the river. The cross-section of river at various points along the river is an important parameter in any dam break analysis problems. Derivation of cross-sections by field survey is a very laborious work, time consuming and costly affair. Alternative methods for arriving cross-sections are to be investigated. In this study, the approximate cross-sections are derived from SRTM DEM (Digital Elevation Model) and are adjusted in the river reach so that the solutions of unsteady flow model converge.

Another important parameter is the maximum probable flood. There are many methods for the computation of flood from a river basin. Clark's IUH method is one of the most common methods used to find unit hydrograph and from which the flood hydrograph of the basin may be derived. One of the parameters used to derive the instantaneous unit hydrograph using Clark's method is the storage constant, k.

The storage constant is generally obtained by plotting the recession limb of observed flood hydrograph. In this study no observed flood hydrograph data were available for the river. Hence a geomorphological based approach is adopted for the estimation of k.

The Dam break analysis was done using HECRAS software and inundation map was prepared using HECGeoRAS software. The probable maximum flood required for the dam break analysis was determined using GIUH based Clark's method.

II. REVIEW OF PREVIOUS STUDIES CONDUCTED

Dams are considered "installations containing dangerous forces" .Dam failures are comparatively rare, but can cause immense damage and loss of life and properties when they occur. Being one of the most destructive failures, a wide range of studies have been conducted on this regard.

Xu Y et al.,(1983) have developed empirical formulas with physical meaning for predicting dam breaching parameters based on past dam failure data. Databases of 182 earth and rockfill dam failure cases have been compiled; among these cases nearly one-half are for large dams higher than 15 m. A multi parameter nonlinear regression model was used to develop empirical relationships between five breaching parameters.

MacDonald C T et al., (1984) have analyzed data collected on a number of historical dam failures and graphical relationships for predicting breach characteristics were developed for erosion type breaches. The data provides a basis for selecting a breach shape and calculating the breach size and the time for breach development. A relationship was also developed for estimating peak outflows from dam failures. This relationship can be used to verify the methodology and the results of dam safety studies.

Cameron T et al.,(2008) have done a Dam break analysis of Hawaii dam. Dam break study consists of precipitation analysis, hydrologic modeling, dam break flood routing and inundation mapping of resultant flood. Hydrologic modeling was performed with the HEC-HMS. Dam breach analysis and flood routing flood wave was performed with HEC-RAS software. Inundation mapping was prepared using HECgeoRAS

Justin M et al.,(2008) have presented a synopsis of the guiding regulations and the process of creating georeferenced, spatially accurate inundation maps and also the recommendations for developing clear, concise dam break inundation maps using the Hawaii Dam break technical studies as a case study. The benefits of developing georeferenced inundation mapping files were also mentioned.

Yochum S E et al., (2008) have developed a HEC-RAS unsteady flow model to predict the movement of a dam breach flood wave through the downstream valley of Big Bay Dam embankment. High water marks were measured shortly after the failure. HEC-RAS performed well with relatively accurate agreement of predicted high water levels with measured high water marks

In all the above studies, the various effects of dam failure are evaluated using different sofwares and varying the conditions of failure. In the present study, HECRAS is used to carry out the Dam Break analysis. Digital elevation model is made use to extract the river cross-section. For dam break analysis Probable Maximum Flood (PMF) is calculated using GIUH based Clark's method and synthetic unit hydrograph method.

III. METHODOLOGY

This study deals with the dam break analysis of Malankara dam using HEC-RAS. For the dam break analysis, geometric data and flow data is required. Geometric data can be developed using GIS and HECGeoRAS software. Determination of flow data includes the calculation of Probable Maximum Precipitation (PMP), Probable Maximum Flood (PMF). In this study, PMP was calculated using Intensity-Duration-Frequency curve and PMF was determined using Geomorphological Instantaneous Unit Hydrograph based Clark's method.

A. Determination of Maximum Probable Precipitation (PMP) using IDF curves

The daily rainfall data for 29 years were collected. The magnitude of maximum values of 24 hours, 48 hours and 72 hours duration rainfall values were derived for each year from 30 years daily rainfall data. The probable maximum rainfall was calculated for different return periods using Gumbel's extreme value (I) distribution. IDF curves were plotted for different return periods, and used for finding the intensity of rainfall for any duration and any return period.

The duration of rainfall to be used for determining PMP from IDF curves was obtained by computing time of concentration, T_c for the basin. T_c was determined using Kirpich's equations. The effective slope and length of basin required for computation of T_c was derived using GIS analysis with the help of drainage network and SRTM DEM.

B. Determination of Maximum Probable Flood (PMF) using Geomorphological Instantaneous Unit Hydrograph (GIUH)

Clark's method was used for developing an IUH due to an instantaneous rainfall excess over the catchment. In this method isochrones showing lines of equal travel time to the outlet of the basin were drawn and inter-isochronal areas were obtained from which a time area diagram was drawn. The inter-isochronal areas were obtained using GIS analysis. The hydrograph obtained using time area method was routed using Muskinghum method. In the Muskinghum method the storage coefficient k is an important factor and generally computed from the observed hydrographs of the basin. But in this study no hydrograph was available, hence a geomorphological approach was adopted to obtain the value of storage coefficient, k.

In this method a Geomorphological Instantaneous Unit Hydrograph (GIUH) was derived with the help of parameters derived using GIS analysis of the basin. GIUH is a physically based method which uses the Geomorphological parameters to simulate sub basin runoff. The derivation of GIUH, while incorporating the fundamental concepts of linearity and time invariance, is based on Horton's geomorphic laws of stream order of the sub basin and can be interpreted as the probability density function of the travel time to the sub basin outlet of a drop of water landing anywhere in the sub basin.

Peak and time to peak characteristics of the GIUH can be expressed as a function of Horton's order ratios as given in equation 1 and 2 [2]

$$q_p = \frac{1.31 R_L^{0.43} V}{L_\Omega} \qquad (1)$$

$$t_p = 0.44 (L_\Omega/V)(R_B/R_A)^{0.55}(R_L)^{-0.38} \quad (2)$$

Where, q_p is peak flow in units of inverse hour, tp is time to peak in hour, R_B, R_L, R_A are bifurcation, length and area ratios given by the Horton's laws of stream numbers, lengths and areas respectively, L is length in km of the highest order stream and V is a dynamic velocity parameter

The storage constant, k required for the study was determined using GIUH based Clark's model. GIUH based Clark's model was derived using non-linear optimization procedure [5] as explained below.

1. Geomorphological parameters like R_A, R_B and R_L for consecutive orders and the overall values of these parameters for the catchment were evaluated as a whole

   Bifurcation ratio (R_B) was computed using Horton's law of stream numbers which states that the number of stream segments of each order form an inverse geometric sequence with order number. Mathematically it can be expressed as given in equation 3

   $$R_B = \frac{N_i}{N_{i+1}} \qquad (3)$$

   N_i and N_{i+1} are the number of streams in order i and i+1 respectively

   Stream-length ratio, R_L was computed using Horton's law of stream length which states that the mean lengths of stream segments of each of the successive orders of a basin tend to approximate a direct geometric sequence. R_L can be calculated using equation 4.

$$R_L = \frac{\overline{L_{i+1}}}{\overline{L_i}} \tag{4}$$

$$\overline{L_i} = \frac{1}{N} \sum_{j=1}^{N_i} L_{i,j}$$

Where L_i is the average length of channel of order i
Stream-area ratio, R_A was calculated using the equations 5 and 6

$$R_A = \frac{\overline{A_{i+1}}}{\overline{A_i}} \tag{5}$$

$$\overline{A_i} = \frac{1}{N} \sum_{j=1}^{N_i} A_{i,j}$$

$$\tag{6}$$

Where, A_i is the area of the watershed that contributes to the channel segment of order i and all lower order channels, $\overline{A_i}$ total area that drains into the stream of order i

2. Peak velocity V for the highest rainfall excess was estimated using equation 7

$$T_c = 0.2778 L/V \tag{7}$$

3. Peak discharge was calculated using the equation 1
4. Two trial values of the storage coefficient of GIUH based Clark model were assumed as k_1 and k_2, then the ordinates of two IUHs were computed by Clark's model
5. Peak discharges Q_1 and Q_2 of the IUHs obtained for Clark model for the storage coefficients k_1 and k_2 were found out
6. The value of objective functions were computed using equations 8 and 9

$$FCN1 = (q_P - Q_1)^2 \tag{8}$$

$$FCN2 = (q_P - Q_2)^2 \tag{9}$$

7. The first numerical derivative FPN of the objective function FCN was computed with respect to k

$$FPN = \frac{FCN1 - FCN2}{k_1 - k_2} \tag{10}$$

8. The next trial value of k was determined using the following governing equations of Newton–Raphson's method (equation 11)

$$\Delta k = \frac{FCN1}{FPN} \tag{11}$$

$$k_{new} = k_1 + \Delta k$$

9. For the next trial, $k_1 = k_2$ and $k_2 = k_{new}$ .the procedure was repeated till one of the following criteria of convergence was achieved

   ▪ FCN2= 0.000001

   ▪ No. of trials exceeds 200

   ▪ $\left| \frac{\Delta k}{k_1} \right| = 0.001$.

10. The final value of storage coefficient k_2 obtained as above is the required value of the parameter k corresponding to the value of time of concentration t_c for the Clark model
11. The IUH using the GIUH based Clark model with the help of final values of storage coefficient k was computed

The IUH ordinates were then converted into 1 hour unit hydrograph by S- curve method. The PMP values obtained using IDF curves were used to determine the rainfall excess. The design base flow, loss rate, conversion factor for converting 24 hours rainfall to short duration conversion factor for areal reduction were selected from CWC flood estimation report for West Coast Zones 5 (a) & 5 (b). The direct runoff ordinates were obtained by multiplying rainfall excess with UH ordinate and adding the base flow with direct runoff ordinates, the flood hydrograph was derived.

C. Dam Break Analysis

Unsteady flow model was developed using HEC-RAS to predict the movement of a dam breach flood wave through the downstream. GIS data development was done using HECGeoRAS. Raslayers such as stream centerline, cross sectional cutlines, flow path line, bank line, storage area, inline structure etc were created. Attribute data and elevation data was extracted from Triangulated irregular network, TIN was developed for the study area using SRTM DEM. SRTM DEM was adjusted in the river reach so that the solutions converge. Then RAS import file was generated and imported. Geometric data, breach data and unsteady data were entered for the unsteady analysis. After the analysis, results were exported to HECGeoRAS for the post processing of results.

Results obtained after the unsteady analysis in HEC-RAS, was imported to GIS. When it was imported to GIS, bounding polygon get created which defines the analysis extent for inundation mapping by connecting the endpoints of cross sectional cut lines. Water surface TIN was also generated. For delineating flood plain, water surface TIN was converted to a GRID. Dtmgrid was subtracted from water surface grid. Area with positive results was considered as flood area and area with negative result as dry. All the cells in water surface grid that result in positive after subtraction were converted to polygon, which is the final inundation polygon.

IV. STUDY AREA

The study area considered was the Thodupuzha river basin with the Malankara Dam constructed across it, in Kerala state. The study area, spread across Idukki, Ernakulam and Kottayam districts, has an area of 384.8227 km^2. Latitude is between 9°59'6"N - 9°41'13.2"N and longitude is between 76°54'25"E - 76°35'12.2"E. Fig. 1 shows the study area map.
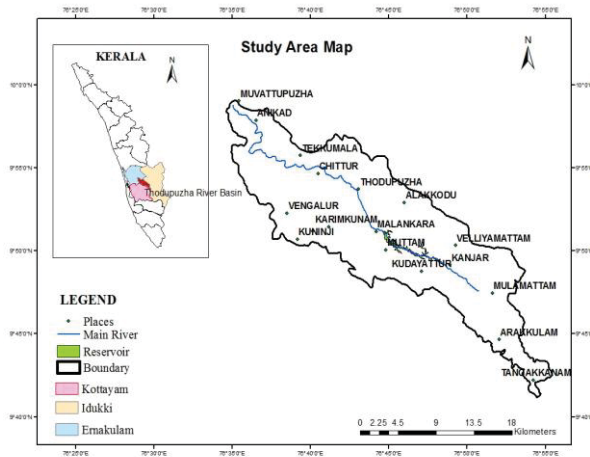

Fig . 1 Study Area Map

V. CALCULATION OF FLOOD USING GEOMORPHOLOGICAL INSTANTANEOUS UNIT HYDROGRAPH (GIUH) BASED CLARK'S METHOD

Maximum Probable precipitation was calculated using IDF curves. IUH ordinates were determined using Clark's method, assuming value of storage constant, k equal to the time of travel. . The actual value of storage constant, k was computed using a non-linear optimization procedure[2], so that peak of the IUH estimated by the Clark model is equal to peak of the GIUH. IUH ordinates were computed using the GIUH based Clark model with the help of final values of storage coefficient k. Then using the obtained GIUH, flood hydrograph was developed.

29 years daily rainfall data of Thodupuzha station was collected. The magnitude of maximum values of 24 hours, 48 hours and 72 hours duration rainfall values were then computed for each year. The probable maximum rainfall was calculated for different return periods using Gumbel's extreme value distribution. Using the obtained values of maximum rainfall intensities and durations, Intensity-Duration-frequency curves for different return periods were plotted. Fig. 2 shows the IDF curves for return periods, T= 100 years, 200 years, 400 years, 1000 years. From the figure, it can be observed that intensity decreases with increase in time. Maximum intensity value was obtained as 1.6178 cm/hr for T=1000 years and duration=24 hours.

Length of the longest drain was obtained as 28330.6489 m and effective slope as 0.0193396. Using these values time of concentration was calculated and obtained as 3.9735 hours. For drawing isochrones, points of equal time of travel were

found out, and then lines were drawn connecting those points. In this study, isochrones were drawn for time of travel (0.33,0.67,1,1.33,1.67,2,2.33,2.67,3,3.33,3.67,4) hours. Inter-isochronal areas were found out using ArcGIS software. Using the inter-isochronal areas and time-histogram was plotted. Fig.3 shows the isochronal areas. Fig. 4 shows the time area histogram.
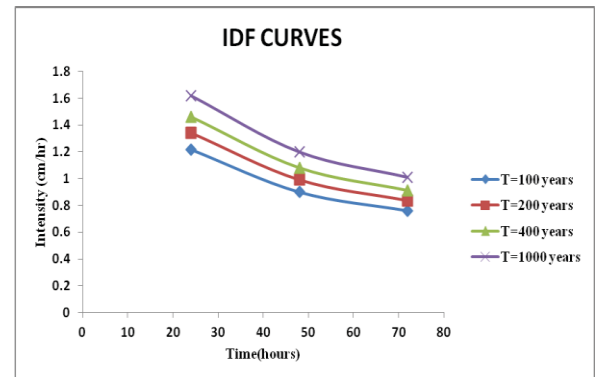

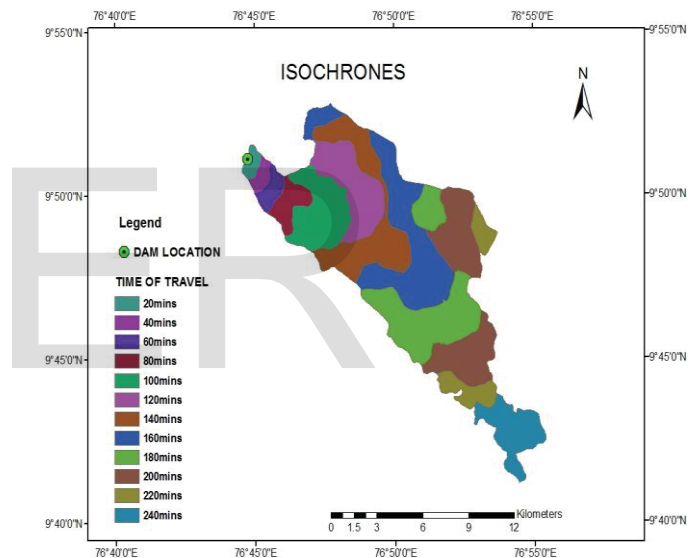Fig. 2 Intensity-Duration-Frequency curves for different return periods

Fig. 3 Isochrones

From the IDF maximum intensity value 1.6178 cm/hr was obtained when the return period is 1000 years and duration is 24 hrs. As per CWC flood estimation report for west coast zones 5(a) and 5(b), the loss rate was 0.19 cm/hr and the design base flow was 0.15 cumecs/ km^2. Subtracting the loss we get the intensity as 1.4278 cm/hr ie 34.2 cm. Area of the catchment is 142.8167 km^2. Therefore, base flow becomes 21.423 cumecs.

Using the conversion factor and areal reduction factor given in the CWC report, 24 hours duration point rainfall was converted to 3.9735 hours areal rainfall. The 3.9735 hour duration areal rainfall was obtained as 16.308 cm.

Storage time constant, k was assumed as equal to the time of travel which is 0.33 hours. The inflows at various times were calculated and routed by the Muskingum method. Instantaneous unit hydrograph was obtained. Then the actual value of storage constant was calculated by equating the peak of the IUH estimated by the Clark model and peak obtained using GIUH approach. For this, GIUH parameters were estimated. $R_B=4.6468$; $R_L=2.6812$; and $R_A= 5.36336$. Velocity was obtained as 1.9806 m/s.
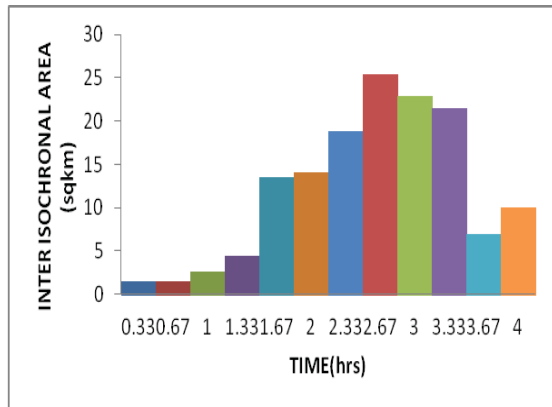

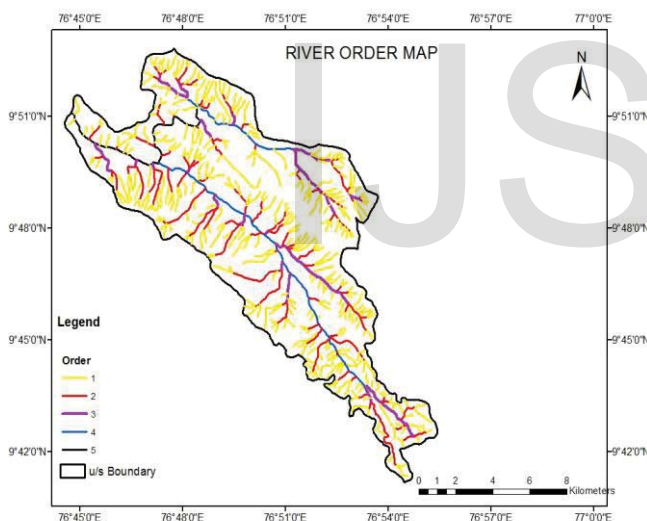Fig .4 Time-Area Histogram

Fig. 5 River order map

Peak value of GIUH (q_p) calculated using equation 1 was obtained as 145.925 cumecs.   Storage constant, k was determined using non-linear optimization procedure [5] and obtained as 1.1827 by iterating until convergence was achieved. Using this value of k, GIUH ordinates were calculated.1 hr unit hydrograph ordinates were determined using GIUH ordinates. Flood hydrograph ordinates were calculated. Fig.5 shows the river order map. Fig. 6 shows the GIUH. Fig. 7 shows the flood hydrograph.

Fig.6 Geomorphological instantaneous unit hydrograph

Fig.7 Flood hydrogtaph obtained using GIUH based Clark method

VI. DAM BREAK ANALYSIS

Triangulated irregular network (TIN) was developed for the study area from SRTM-DEM. Elevation values were adjusted in the reach so that the solutions converge. Fig. 8 shows the TIN developed for the study area. For the GIS data development using HECGeoRAS, raslayers such as stream centerline, cross sectional cutlines, flow path line, bank line, storage area and inline structure were created. Attribute data and elevation data was extracted from TIN developed for the study area. Then RAS import file was generated. New HECRAS project was created, RAS import file was imported. Imported geometric data is shown in Fig. 9.

Cross sectional data was modified using a channel modification tool provided in the HECRAS. A dam was modeled in HEC-RAS as an inline structure. An inline structure was represented with a weir profile (that includes the spillway) and gates for normal low-flow operation

To model a dam failure in RAS, failure mode, breach size, and breach time was entered. Failure mode was selected as overtopping. Breach width and Breach formation time were given as 30m and 0.2 hours respectively. Shape of the breach was assumed as rectangular.
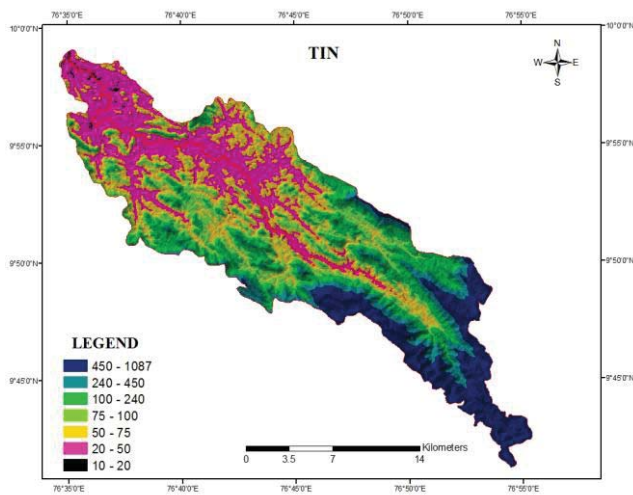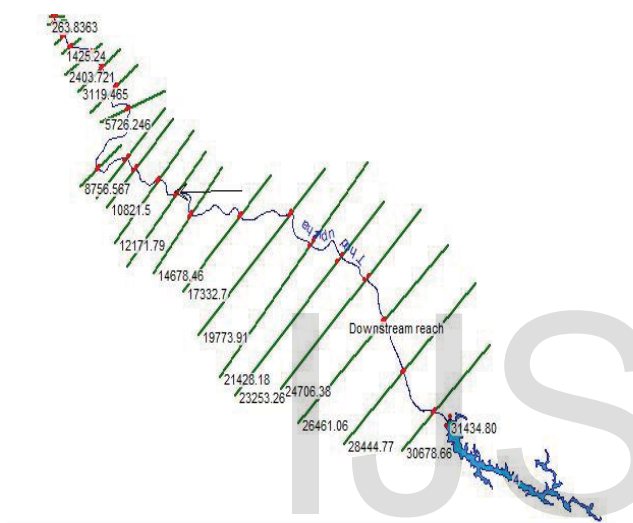
Fig.8 TIN

Fig. 10 Profile plot

Fig. 9 Geometric data created for study area using HECGeoRAS

Fig. 11 Flow-stage hydrograph of RS 26461.06

Fig.12 shows the inundation map prepared. From the flow inundation map prepared it is possible to evaluate the area of inundation and is found to be 41.6773 km^2 and the total time travel of the flood wave is 39 hours to cover a distance 36 km.

Flow data was entered. Upstream boundary condition was given as flow hydrograph, which is obtained using GIUH based Clark's method. Downstream boundary condition was given as normal depth. Initial flow through downstream was given as 100 cumecs. Initial storage elevation was given as +43.00m.

Unsteady flow analysis was done. Flow and stage hydrograph for different cross sections were obtained. The profile plot obtained after the analysis is as shown in Fig. 10. Fig.11 shows the flood- stage hydrograph obtained for river station 26461.06
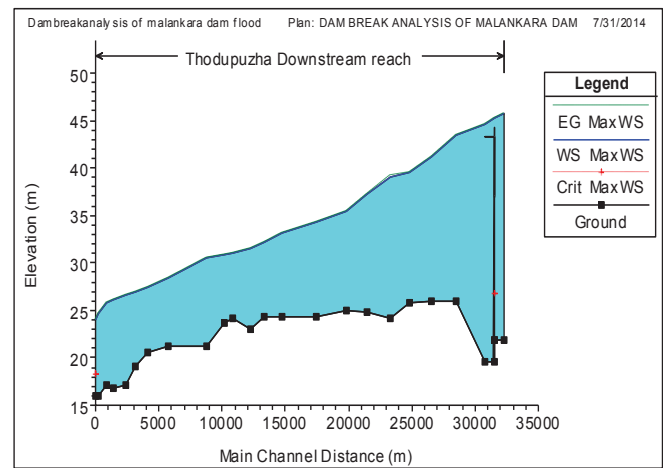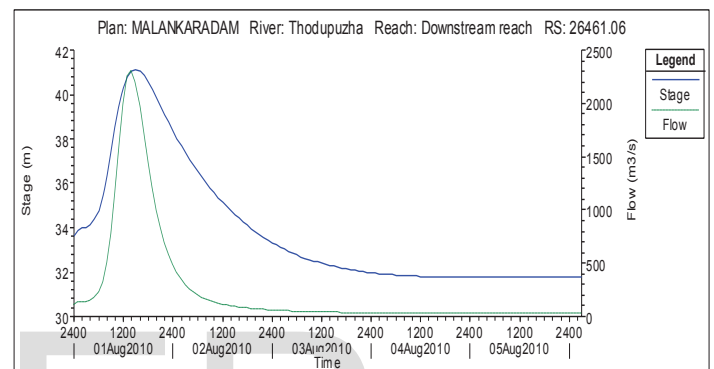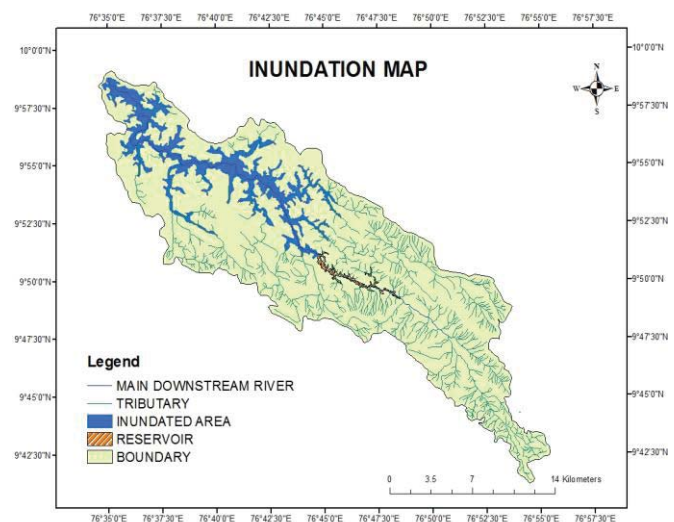

Fig.12 Inundation map

VII. CONCLUSION

In this study, dam break analysis is done for Malankara dam. The various inputs for the analysis such as Maximum Probable Precipitation (PMP), Maximum Probable Flood (PMF), river cross-sections etc are derived. The maximum probable precipitation is derived using IDF curve method. The flood computation is done using GIUH based Clark's method. The river cross-sections are derived using SRTM DEM. The dam break analysis is done using HECRAS and HECGeoRAS software and the inundation map is prepared. The conclusions of the study are

1. The maximum probable precipitation is obtained as 388.272 mm (24 hours duration rainfall)
2. The probable maximum flood is obtained as 2848.80 cumecs
3. The spillway provided for the dam is adequate to carry the maximum probable flood
4. The time of travel of flood wave through the downstream is 39 hours
5. The area of inundation for a flood of 2848.80 cumecs is 41.7 sq.km

This study demonstrated the use of HECRAS and HECGeoRAS software for the dam break analysis and DEM derived cross-sections can be used for such analysis. However, the results obtained are not compared with that of actual cross-sections surveyed for the area.

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