DAM BREAK FLOOD WAVE ANALYSIS FROM UKAI DAM IN LOWER TAPI RIVER, INDIA

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ABSTRACT

In present study, two-dimensional (2D) hydrodynamic (HD) simulation of dam break flood wave, generated from Ukai Dam in Lower Tapi River (LTR), is presented for flood risk assessment in Lower Tapi Basin (LTB), including Surat city which is one of the highly populated cities in Gujarat, India. The one-dimensional (1D) HD model is used to simulate the failure of Ukai dam to obtain the dam break flood hydrograph for different scenarios. The inflow of year 2006 with peak discharge 34118.3 m3/s and tidal level at Arabian Sea, has been used as upstream and downstream boundary conditions respectively. The dam break flood hydrograph obtained from 1D model has been subsequently used as input for 2D HD model, to simulate the dam break flood wave across the entire LTB. Ukai dam was considered at the reservoir level of 105.156 m (FRL) above mean sea level during the dam break suggested by Froehlich (2008). The simulated dam break flood with peak discharge of 57208.9 m3/s (with maximum velocity of 11.4 m/s), which is about 1.68 time higher than inflow peak was considered for 2D HD modelling to investigate the area under submergence in LTB. More than 30% of area across the LTB gets submerged for the said scenario whereas entire Surat city was inundated with aforesaid condition. The methodology adopted in the dam break flood wave analysis using 2D HD model is generic and can be applied to similar geographical conditions in other parts of the globe.

1. INTRODUCTION

The multipurpose dams, creates a pool of reservoir to serve many purposes such as irrigation, water supply, power generation flood control and recreation etc. whereas the failure of such structure can lead to the severe consequences. The sudden failure of dam is often catastrophic, releasing large volume of water in shorter duration resulting in colossal flooding situation for the habitats situated in the downstream floodplain. The devastating floods due to failure of such structure were observed in many parts of the world (You et al., 2012). Further, global warming has been responsible for increase in frequency of flood and extreme precipitation significantly (Milly et al., 2002). Many dams constructed in the past are facing the problem of higher inflow than design flood due to increase in runoff resulted from changes in climate and anthropogenic activities (Mallakpour et al., 2019). As per Central Water Commission (CWC) (http://cwc.gov.in/damsafety/dam_fail_india accessed on December 10, 2019), total 36 dam failure events were recorded in India of which failure of the Machhu-II dam (Gujarat) in the year 1979 was the worst recorded incident, results in loss of more than 2000 lives. The guidelines for mapping of flood risk associated with dams (https://www.damsafety.in/ecm-includes/PDFs/Guidelines_for_Mapping_Flood_Risks_Associated_with_Dams.pdf accessed on date December 12, 2019) were published by the CWC in year 2018. The "Dam Safety Bill" was passed in the Lok Sabha by Government of India (July 29, 2019) while considering the importance of dam safety, prevention of dam failure related disaster and to ensure the safe functioning of dam across the country. Thus, dam break modelling is an important aspect in the planning of such major structures to identify the critical and strategic infrastructure in the downstream of dam and develop the flood risk mapping of the region.

The one-dimensional (1D), two-dimensional (2D) and 1D-2D integrated hydrodynamic (HD) modelling are the popular tools to simulate the various flooding scenarios. Many researchers (Pramanik et al., 2010; Mah et al., 2011; Timbadiya et al., 2014a; Yamini et al., 2016; Vora et al., 2018) developed 1D modelling to accomplish various objectives such as performance evaluation of developed model, establish the stage discharge relationship and prioritization of flood embankment etc. for their respective study areas. The 2D and 1D-2D integrated modelling (Lindner and Miller, 2011; Timbadiya et al 2014b; Liu et al., 2015; Matte et al., 2017 and Salunkhe et al. 2018) were developed to identify the area under submergence when water overtops the river bank to get better understanding of inundation statistics across the floodplain. Similarly, the understanding of dam breach phenomenon based on past studies such as MacDonald and Langridge-Monopolis, (1984) developed the graphical relationships to estimate the dam breach parameters (breach width, shape and formation time). The mathematical expressions were developed for the expected value of aforesaid breach parameters, based on data of 74 embankment dam failure events (Froehlich. 2008). Many researchers modelled the dam break flood behavior by using different approaches such as, the 1D model developed to study the failure of Big-Bay dam in 2004 (Yochum et al., 2008) and Gleno dam in 1923 (Pilotti et al., 2010) with the help of available data to them. Similarly, 2D modelling approach were used to investigate the failure of, St. Francis dam (Begnudelli and Sanders, 2007), Baldwin Hills (Gallegoes et al, 2009), Vyasi Hydropower Dam on Yamuna River (Lodhi and Agrawal, 2012) Vajont dam (Bosa and Petti, 2013), Janghyeon and Dongmak (multiple) dam (Kim and Sanders, 2016). Previous investigation cited above, clearly indicate that 1D and 2D models are capable of simulating dam break flood events of high magnitude across the globe. Similar, strategy has been adopted in present study in simulation of dam break problem of Ukai dam located in Tapi reach India.

The Ukai dam is largest multipurpose project on Tapi River, lies within the Lower Tapi Basin (LTB) (Area = 3618 km2). The Lower Tapi River (LTR) covers the length of 128 km from Ukai dam to Arabian sea. The Surat city is a diamond processing hub and textile industry with population of 44,66,826 (as per census of India, 2011) situated on the bank of LTR, 100 km downstream of Ukai dam. Many important industries such as Oil and Natural Gas Corporation (ONGC) of India, National Thermal power Corporation (NTPC), Reliance Industries etc. are also located in the estuary of LTR. The LTR and Surat city has faced many floods after the construction of Ukai dam in 1972, the floods of years 1994, 1998, 2006 and 2013 are recent floods in last two decades due to heavy releases from the Ukai dam. The flood of year 2006 alone inundated the 80% of the city resulting loss of Rs. 21000/- crore and more than 150 lives (Patel and Srivastava, 2013). The 1D HD model (Timbadiya et al., 2014a), 2D model (Ramirez et al., 2016) and 1D-2D integrated model (Timbadiya et al., 2014b; Patel et al., 2017) were developed in order to study the behavior of 2006 flood under different scenarios. Vora et al. (2018) suggested the prioritization of the flood protection levees along the LTR. The past studies of flood modelling were considered the release from Ukai dam whereas, the studies are not available in literature for simulating the effect of Ukai dam break flood and its effect on downstream habitat. The present investigation of Ukai dam break flood modelling broadly comprise of the following objectives: (i) To develop and calibrate 1D-HD model for Lower Tapi River and simulate dam break scenarios to obtain the corresponding dam break flood hydrograph just downstream of Ukai dam. (ii) To develop 2D-HD model to simulate the propagation of dam break flood wave from Ukai dam to obtained the area under submergence across LTB and Surat city, in particular. The results of the present study would be useful in development of flood hazard and risk maps, identifying the location of critical infrastructure, evacuation time and route etc. for the Surat city and its outskirt area in future.

2. MATERIALS AND METHOD

2.1 Study Area

The Tapi River originate from Multai in Betul district of Madhya Pradesh, at an elevation of 752 m. It passes through three different states of the country as Madhya Pradesh, Maharashtra and Gujarat by covering the total area of 65,145 km^2. The 724 km long river partitions the total area into three sub-basins viz. Upper Tapi basin from origin of the river to the Hathnur Dam (29, 430 km^2), Middle Tapi basin from Hathnur Dam to Ukai Dam (32, 097 km^2) and Lower Tapi basin from Ukai Dam to Arabian Sea (3,618 km^2) (CWC 2014). The Ukai Dam is the large multipurpose project completed on the Tapi River in year 1972. It is the composite structure with total length of 4927 m inclusive 425 m long spillway. The Full Reservoir Level (FRL) and Top of the dam are at 105.156 m and 111.25 m above mean sea level respectively with capacity of 7414 Mm^3 live storage. The salient feature of the Ukai dam are given in Table 1. The Surat city is situated on the bank of Lower Tapi river around 100 km downstream of the Ukai dam. Surat is second largest city in Gujarat, biggest textile hub, diamond cutting center and administrative capital of the state. The Surat city spread over the area of 326.51 km^2. The detailed layout of the study area for the analysis of Ukai dam break investigation with location of dam and gauging stations shown in Figure 1.

2.2 Data Source

The river cross-sections in 3D AutoCAD contour map were collected from Surat Municipal Corporation (SMC) for the river stretch of Ukai dam to Arabian Sea. The detailed configuration of major control structure along Lower Tapi river, Kakrapar weir and Singanpur weir were collected from Surat Irrigation Circle (SIC). The hourly discharge of Ukai dam and Kakrapar weir, Nehru bridge for the year 1980-2008 has been collected from the Nodal officer, Flood Control Cell, SIC. The hourly water level at Mandavi bridge provided by the Superintending Engineer, State Water Data Center (SWDC). The hourly tidal levels were surveyed for the period December 6, 2009 to January 5, 2010 were collected from SIC. The salient feature of Ukai dam were obtained from the Ukai Civil Circle. The contours for Lower Tapi basin were digitized from the Survey of India (SOI) toposheet with 20 m contour interval. The contour map of Surat city and its outskirt area with 0.5 m contour interval were collected from the SMC and SIC respectively. Also, the contours for entire Lower Tapi basin were generated from the SRTM DEM with 10 m interval. The IRS-P6 LISS III image dated February 10, 2009 procured from National Remote Sensing Agency (NRSC), Hyderabad and used for the land use land cover classification of the study area.

Table 1 : Salient feature of the Ukai Reservoir

Reservoir	Reservoir Spillway crest	91.14 m
	Full Reservoir Level (FRL)	105.156 m
	High flood level	106.99 m
	Top of the dam	111.25 m
	Road width on the spillway	6.706 m
	Gross storage capacity at FRL	8511 Mm^3
Hydrology	Observed maximum flood at the dam	42470 m^3/s
	Design flood	49490 m^3/s
	Probable maximum flood	59920 m^3/s
	Maximum regulated outflow from the reservoir	24100 m^3/s
	Total land under submergence	97930 ha

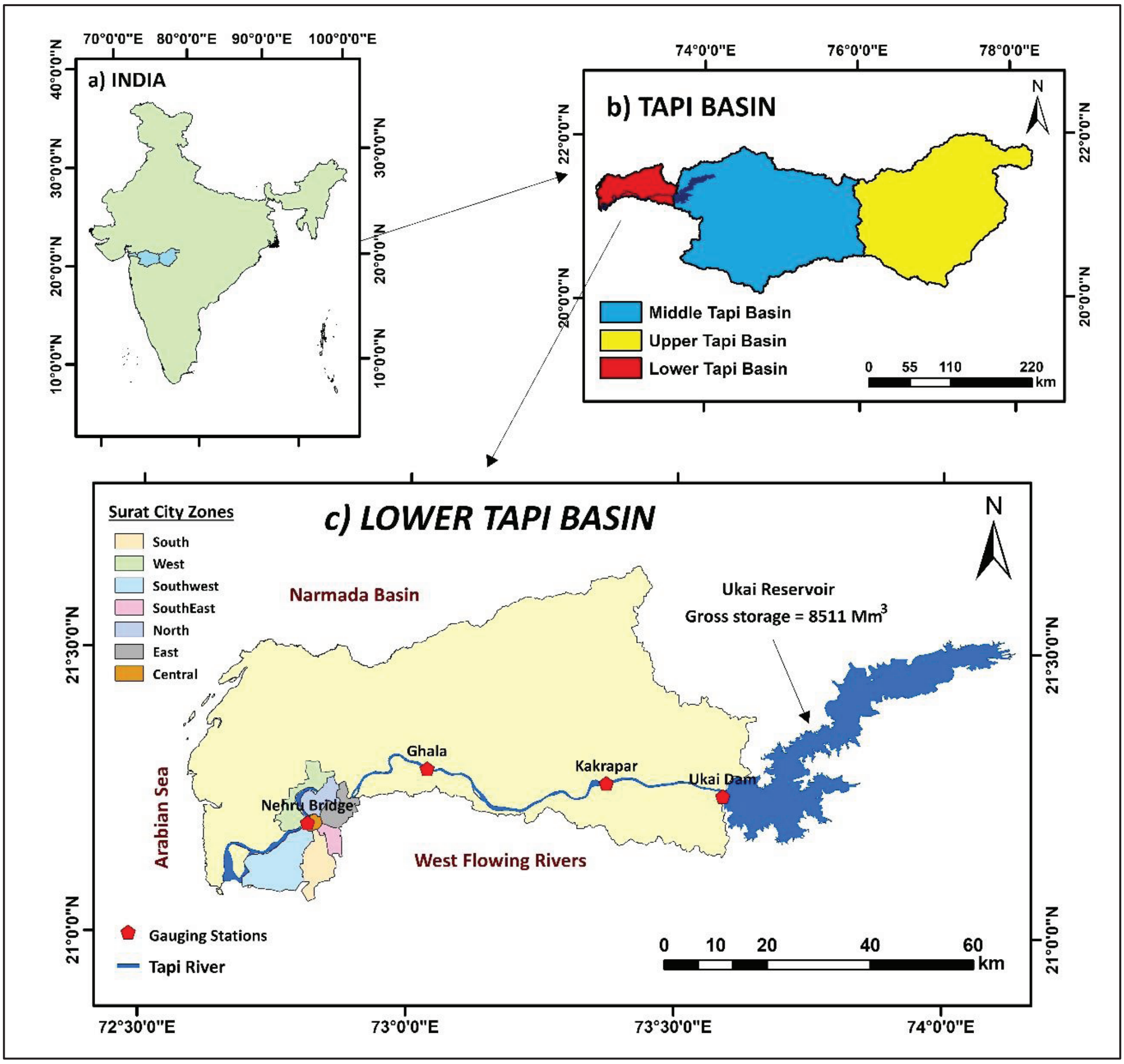


Figure 1 : Index map of Lower Tapi Basin.

3. MODEL DEVELOPMENT

The detailed methodology adopted in the present study consist of two major steps shown in Figure 2.

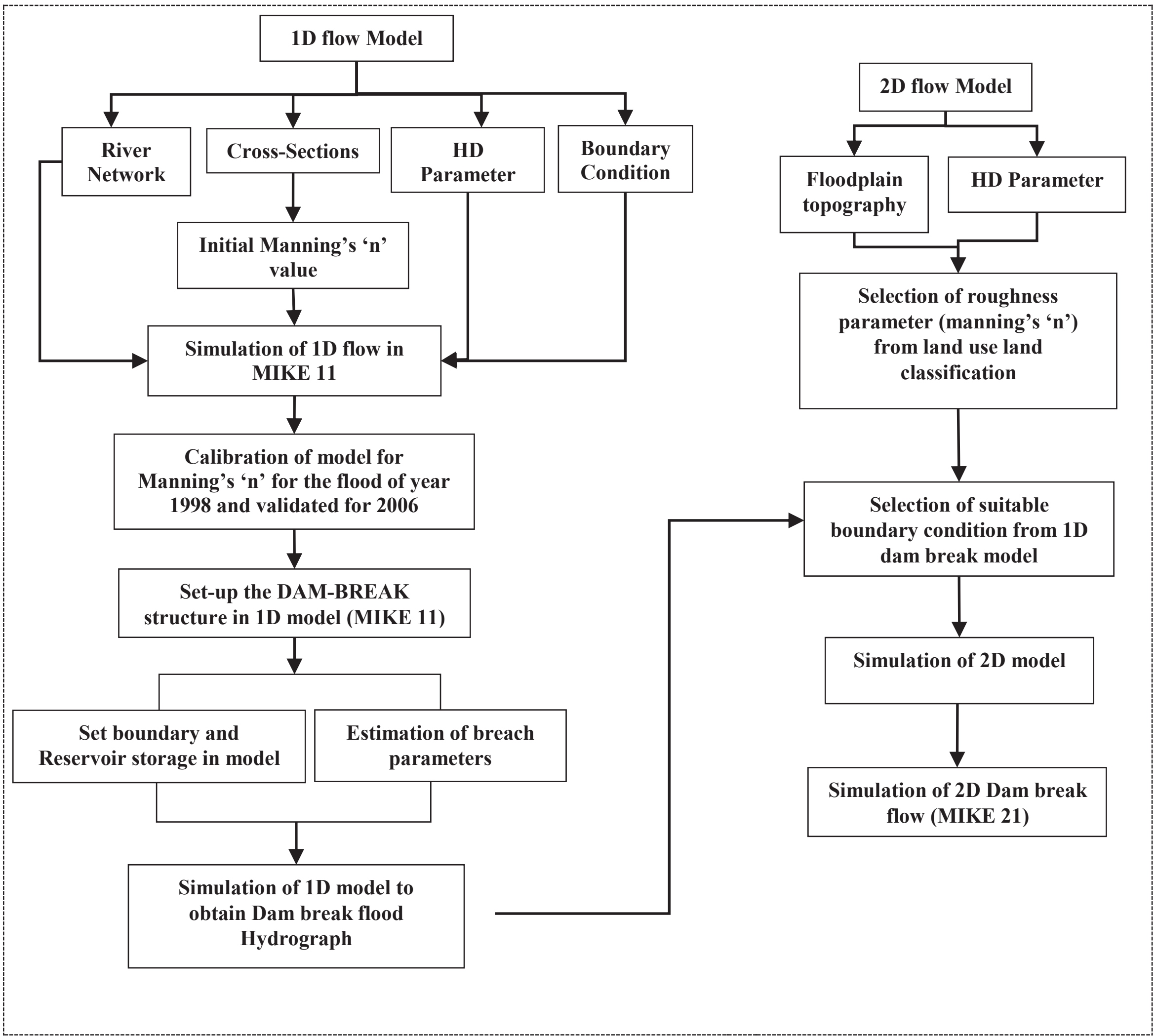


Figure 2 : Flowchart for the methodology adopted in the present investigation

3.1 1D HD Model in MIKE 11 and its Calibration

The 1D HD model in MIKE 11, which is capable of unsteady non-uniform simulation, solves 1D Saint-Venant equation using six-point Abbott-Ionescu finite difference scheme (DHI, 2013a). The 1D model developed for the river stretch of Ukai dam to Arabian Sea, with two existing structure Kakrapar weir and Singanpur weir. Total 190 cross sections were used in the model, the lowest point of each cross-section identified and joint to form the thalweg line of the river. For calibration of the model, hourly discharge from the Ukai dam and Tidal level at the Arabian sea were used as upstream and downstream boundary condition respectively for flood simulation of event 1998 and validated for the event of 2006.

The 1D HD model has been calibrated manually for the channel roughness (Manning's 'n'), the range of river roughness co-efficient adopted as per the guidelines given by Chow, (1959). The comparison of observed and simulated water level to obtain the Root Mean Square Error (RMSE) at Kakrapar, Ghala and Nehru bridge gauging stations (Table 2) has been done and found 'n = 0.03' as an optimize value for the simulations. The results of calibration process ('n' = 0.03) are in agreement with previous studies (Timbadiya et al 2014a) performed on the same river stretch.

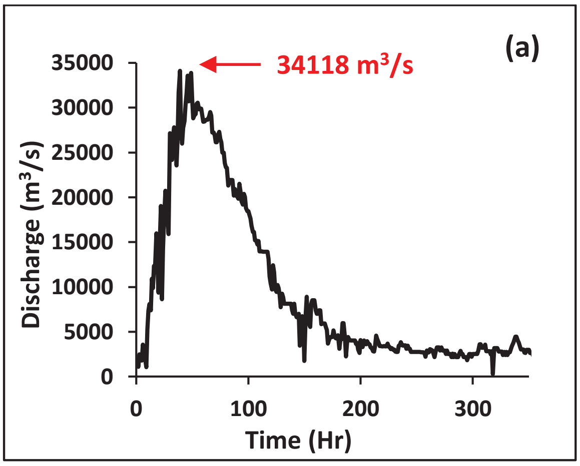
Table 2 : Calibration of Manning's 'n' for the Lower Tapi River

Year	Manning's 'n	RMSE			
		Kakrapar	Ghala	Nehru Bridge	Weighted RMSE
1998	0.02	1.095	2.406	1.941	1.722
	0.025	1.109	1.751	1.168	1.240
	0.03	1.127	1.558	0.847	1.150
	0.035	1.15	1.866	1.124	1.433
2006	0.03	1.240	1.939	0.791	1.200

3.2 Dam-Break Structure in 1D HD Model

The dam break structure added to the (river) network editor in MIKE 11. It allows to define the location of dam, dam geometry, dam failure moment-mode along with selection of dam breach calculation method for the given event. The dam should be located at the Q-point in the separate reservoir branch at which momentum equation are replaced by the equation describe the flow through structure as broad crested weir (DHI 2013a). The inflow hydrograph (upstream boundary condition) of Ukai reservoir for flood of year 2006 (See Figure 3(a)) with peak discharge of 34118.3 m3/s, is considered at the point where dam-break structure has been specified. The Capacity-Elevation curve of the reservoir is used to calculate the additional flooded area which is used to define the reservoir storage (See Figure 3(b)). In the present study for the Ukai dam, failure moment is specified as the reservoir attend the water level of FRL i.e. at 105.156 m. The embankment of the dam breaches due inadequate capacity of the reservoir to hold the inflow and water flows through the breach.

Breach parameters are crucial in determining the outflow hydrograph, downstream of the dam in dam break scenario. Froehlich (2008) determined the breach parameters by fitting the regression analysis on the data obtained from past dam failure events, similar has been used in the present study. The typical sketch of trapezoidal breach developed in dam shown in Figure 4. The values of breach parameters as average breach width (B) in meter, breach slope (z) and breach formation time (tf) in hour with determining equations are given in Table 3.



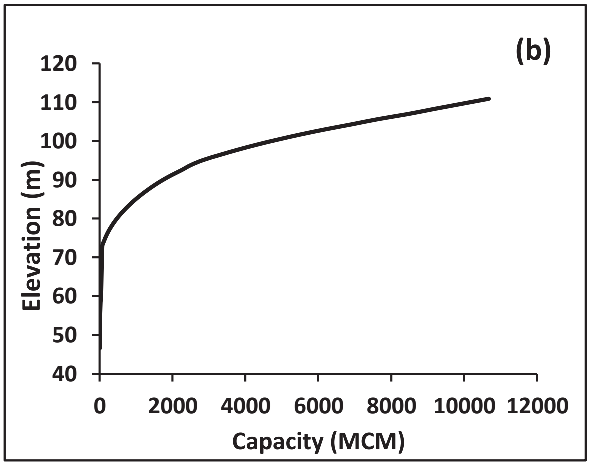


Figure 3 : (a) Hourly inflow hydrograph in Ukai Reservoir during 2006 flood (b) Capacity Elevation curve for Ukai Dam

Table 3 : Breach Parameters based on Froehlich (2008)

Breach Parameter	**Formulae**	**Unit**	**Calculated Value for Ukai Dam for washout of impervious layer**		
			30 %	**50 %**	**75%**
Average width	$B_{avg} = 0.27K_0\ V_w^{0.32}\ H_b^{0.04}$	m	434.3	442.1	448.8
Top width	$B_t = B + H_b z$	m	445.4	453.2	474.0
Bottom width	$B_b = B - H_b z$	m	423.2	431.0	423.6
Side slope	1.0 = Overtopping, 0.7 for other	-	0.7	0.7	0.7

*K_0 = 1.3 for overtopping failure and 1.0 for other failure

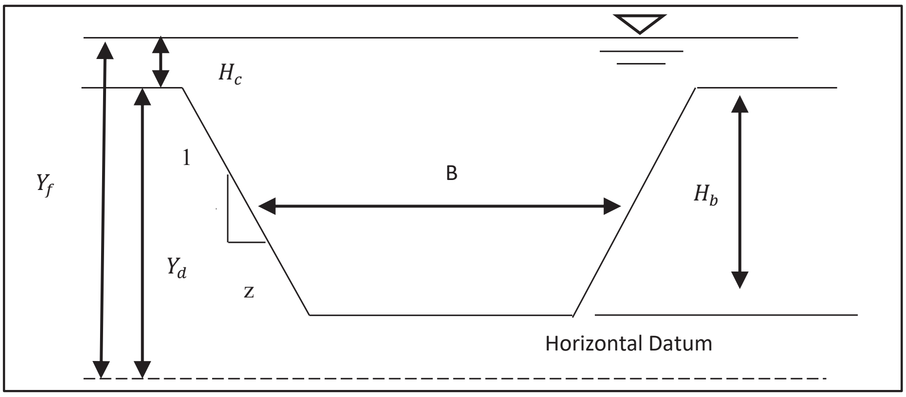


Figure 4 : Typical sketch of Trapezoidal breach in Dam (Froehlich 2008)

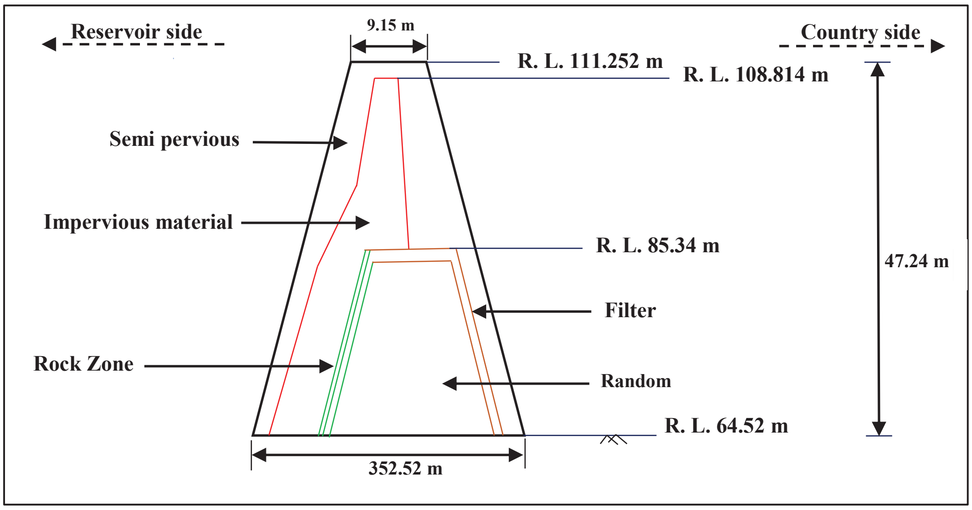


Figure 5 : Cross-section showing material within right bank earth dam- Ukai project (not to scale)

Whereas, Y_f is reservoir water surface elevation at which breach formation begins (m), Y_d is reservoir water surface elevation at top of the breach (m), H_c is critical overtopping depth (m), Vw = Volume of water in the reservoir at the time of failure (m^3) and H_b is Breach height (m). The fully developed breach reaches up to foundation which is more resistant to erosion than embankment material. However, height of breach limited to volume of water in the reservoir at the time of failure or by the presence of a layer of erosion resistant material located in the embankment (Frohlich, 2008). As per the digital maps of Ukai dam received from Ukai Civil Circle, the earthen embankment of dam contains layer of impervious material from bottom of dam to 108.81 m and the rock zone is available up to 85.334 m from the bottom whereas, top of the dam is 111.252 m (See in Figure 5). In the present study of Ukai dam break failure, three scenarios of 30%, 50% and 75% wash out of the impervious layer was considered.

3.3 2D HD Model in MIKE 21

The sudden failure of dam, causes the flood of extreme magnitude and highly unsteady in nature spreads the water from either bank which needs 2D model to evaluate the inundation statistics. To assess the inundation due to dam break flow on the downstream of Ukai dam including Surat city, the 2D hydrodynamic model in MIKE 21 has been developed. The MIKE 21 model with depth-average based numerical solution able to describe the conservation of mass and momentum in two horizontal dimension and simulate the hydraulics for 2D free surface flow (DHI 2013b).

The 2D model required high resolution Digital Elevation Model (DEM) for accurate representation of bathymetry. The DEM of Lower Tapi basin has been created from four different contour data i.e. contours for Surat city and its outskirt area with 0.5 m interval, contours for Tapi river with 1.0 m interval, contours for area Ukai dam to Ghala station were digitized from SOI toposheet with 20 m interval and for the remaining area were generated from SRTM DEM with 10 m interval. All the contours merge together and the raster interpolation tool 'Topo to Raster" in ArcGIS 10.6 has been used to form DEM. The 30m grid size DEM has been used in the present study which is converted to .dfs2 format using Grd2Mike tool in Mike Zero (Figure 6). The distributed roughness parameter for the entire basin obtained by performing the land use land cover (supervised level-1) classification (Anderson, 1976) of the satellite imagery IRS P6 LISS III

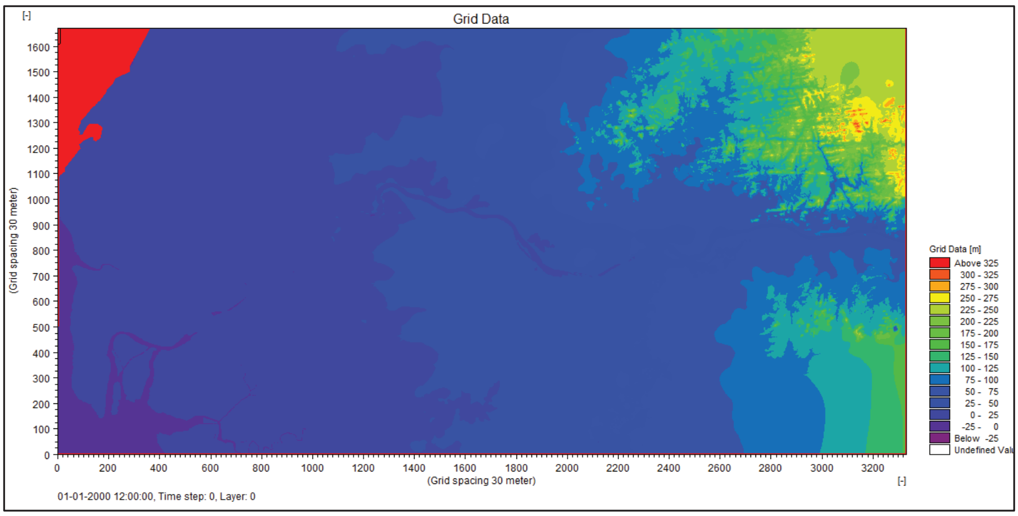


Figure 6 : Bathymetry of the lower Tapi Basin with 30m×30m grid resolution

dated February 10, 2009 in ArcGIS 10.6. The entire study reach divided into six different classes and Manning's 'n' value applied (Chow 1959) viz. agricultural (0.035), forest (0.15), urban (0.15), fallow land (0.04), west land (0.032) and water body (0.03). The value of Manning's 'n' = 0.03 for water body used from the calibration of 1D model. Agricultural area is the most prominent land use within the basin whereas Surat city is the most prominent urban area with population density of 13680 person/Sq. km as per 2011 census (SMC). The dam break flow hydrograph (hourly) obtained from the 1D model used as an upstream boundary condition whereas tidal level at the Arabian sea were used as downstream boundary condition. The velocity of the source (flow) along with direction also need to specified while defining the upstream boundary condition. The one-meter water depth within the channel and dry flood plain is considered as initial condition.

4. RESULT AND DISCUSSION

4.1 Simulation of Dam Break Scenarios in MIKE 11

The analysis of Ukai dam failure is carried out under 1D HD unsteady flow condition to obtain the dam break outflow hydrograph just downstream of Ukai dam. The model is simulated for total 140 hours from the start of inflow. Based on the criteria of development of breach i.e. breach height (H_b), three different scenarios as 30%, 50% and 75% washout of the impervious layer (Figure 5) are considered in the present investigation. The failure moment for the dam is considered as, the water level reaches to FRL (105.156 m) for the given inflow. The reservoir is already filled up to the spillway crest (91.14 m) when heavy inflow came into reservoir and is considered as the initial condition for the reservoir. It takes 18 hr to fill the reservoir from spillway crest to FRL. The designed maximum outflow through the spillway is 46,269 m3/s at HFL. The 78% of the live storage is maintained through radial gates (Total 22 Nos.) installed on the spillway of the dam. hence operation of the gates in such condition is highly critical for the dam safety management. The operational failure of such dam leads to the dam break and directly jeopardize the dam safety. In the present study we assume, reservoir fails due to structural instability resulted from operational failure as water level reaches the FRL against the incoming heavy inflow. The fully developed breach in dam results in outflow hydrograph (Figure 7) with peak discharge of 38127.7 m3/s (maximum velocity = 9.63 m/s), 57208.9 m^3/s (maximum velocity = 11.4 m/s), and 79208.6 m3/s (maximum velocity = 13.45 m/s) for 30%, 50% and 75% washout of the impervious layer respectively.

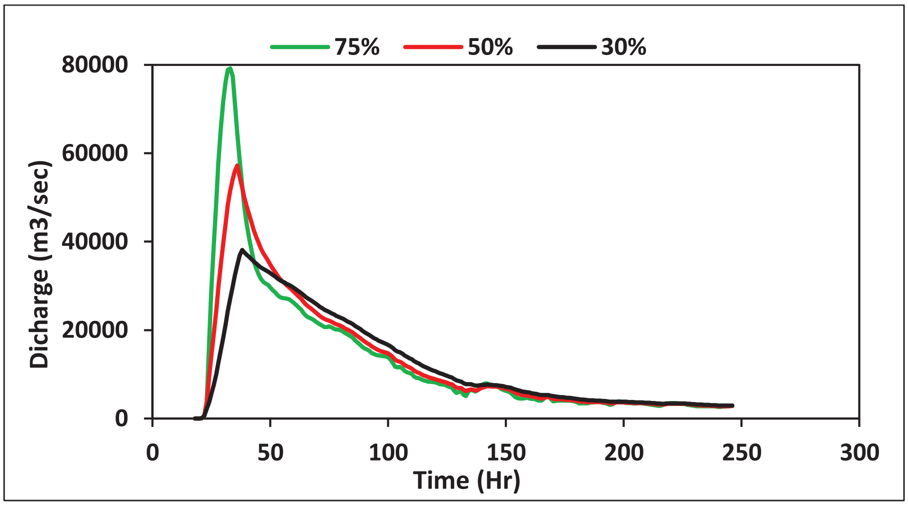


Figure 7 : Dam break Flood Hydrograph for flow through the breach when failure takes place at FRL 105.156 m for different scenarios.

The volume calculated for the dam breach outflow hydrograph against inflow coming into the reservoir, the scenario of 50% washout of impervious layer shows the close agreement with 0.34% volume difference. Also, the breach bottom level (86.41 m) reaches up to the erosion resisting material as rock zone within embankment. The similar scenario is considered in the 2D modelling to obtain the area under submergence across the LTB.

4.2 Simulation of Flood Wave Propagation Due to Dam Break

To find out the inundation due to dam break flow on the downstream of Ukai dam including Surat city, 2D HD model has been developed for area 5007 km^2 (area beyond LTB ridgeline). The dam breach outflow hydrograph with peak discharge of 57208.9 m^3/s with maximum velocity = 11.4 m/s is considered as an input for the 2D model. The 2D model is simulated for total 120 hours from the start of breach in the dam embankment. The flood wave generated from the Ukai dam break flow, overtops both the bank of river and spread across the floodplain. More than 30% of the entire LTB is under submergence. The inundation map with maximum water depth (m) and time required (hours) to attain it, across the flood plain shown in Figure 8 and 9 respectively. The flood inundation maps will be used to find the information on submergence of important structures such as, buildings, roadways, railways etc. whereas travel time of flood wave will be used to evacuate the people from flood prone areas to the safer places.

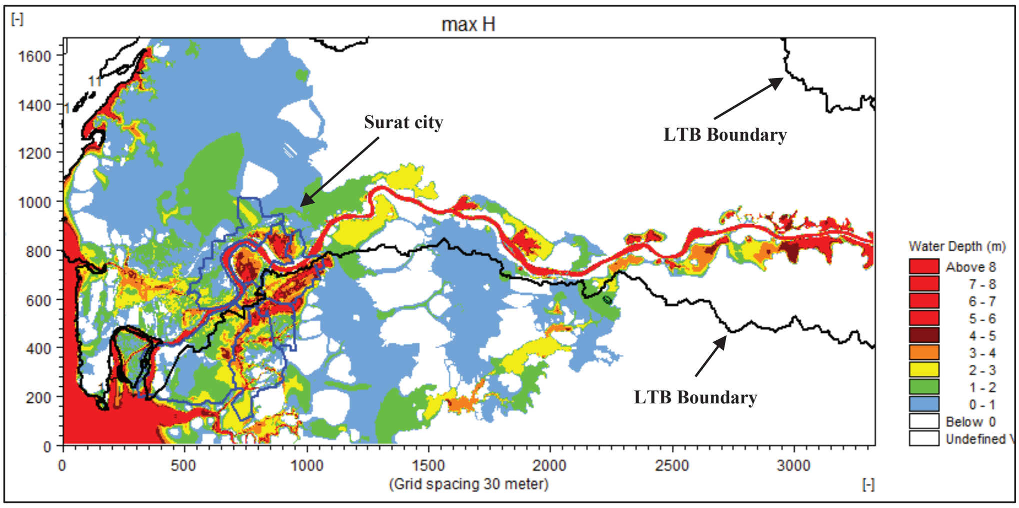


Figure 8 : Inundation across the floodplain (maximum water depth) for Ukai dam break failure

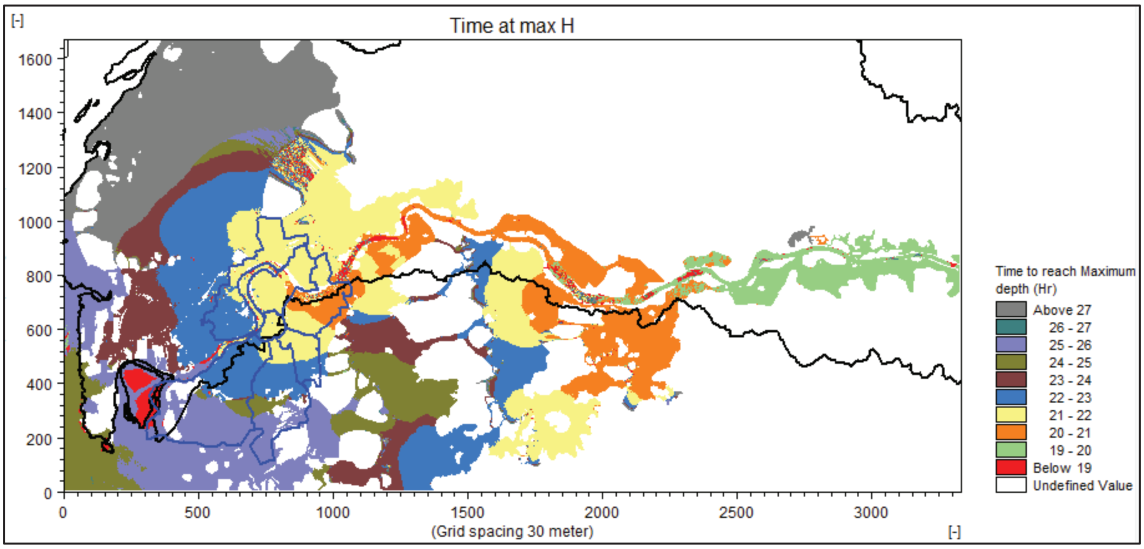
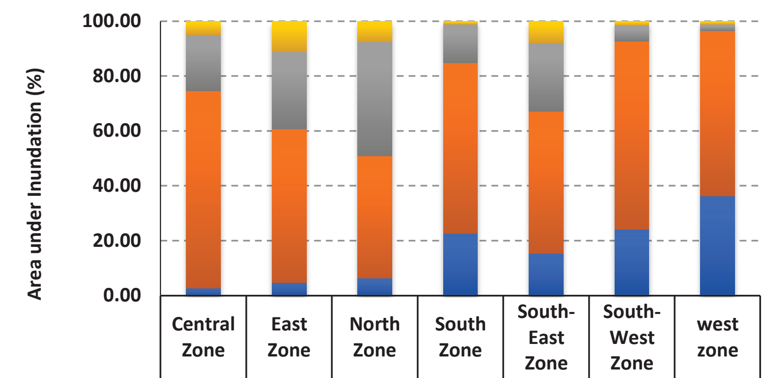


Figure 9 : Map showing time required by flood to attained the maximum water depth across the floodplain

4.2.1 *Depth of Flood Water in Surat City*

The inundation statistics within Surat city has been calculated for the given dam break flood scenario. The inundation depth across the city for all seven zones has been categorized into four ranges viz. (i) water depth less than 1.0 m, (ii) water depth 1.0 m to 3.0 m, (iii) water depth 3.1 m to 6.0 m and (iv) water depth more than 6.0 m. the percentage of area inundated for said dam break flooding scenario shown in Figure 10



	Central Zone	East Zone	North Zone	South Zone	South-East Zone	South-West Zone	west zone
more than 6.0 m	4.92	11.11	7.59	1.18	7.83	1.58	1.22
3.1 m to 6.0 m	20.49	28.21	41.51	13.98	25.08	5.73	2.28
1.0 m to 3.0 m	71.82	56.07	44.64	62.23	51.77	68.74	60.28
less than 1.0 m	2.77	4.61	6.26	22.61	15.32	23.96	36.22

Figure 10 : Zone-wise variation of water depth and area (%) under submergence in Surat city

The analysis shows that, the larger area of each zone (more than 50%) except north zone having water depth in the range of 1.0 m to 3.0m. Some portion of each zone across the city having water depth more than 6.0m which is capable of putting two-story building under submergence. The Central Business District (CBD) area falls in the central zone of the Surat city, of which more than 70 % area gets inundated with water depth in range 1.0 to 3.0 m. The areas which are having water depth less than 1 m needs to be identified from each zone with the help of inundation map. The elevated structures or high rise building from those areas can act as safe-house to shift the people. There is need to identify highly vulnerable areas which are likely to be under maximum submergence with high population density in order to proposed evacuation paths during such catastrophic events.

5. CONCLUSIONS

The development of the suitable hydrodynamic model for the Lower Tapi Basin is the basic need for the future planning and development of the Surat city. The conclusions derived from dam breach flood wave analysis from Ukai dam are as follows-

(i) The hydrodynamic model in 1D have been calibrated for the flood of year 1998 and validated for the flood of year 2006 for the LTR and the optimized value of Manning's 'n' = 0.03 has been arrived.

(ii) Dam break flood hydrograph obtained by simulating model for Ukai dam failure at FRL gives the peak discharge of 38127.7 m^3/s (maximum velocity = 9.63 m/s), 57208.9 m^3/s (maximum velocity = 11.4 m/s), and 79208.6 m^3/s (maximum velocity = 13.45 m/s) for 30%, 50% and 75% washout of the impervious layer scenario respectively.

(iii) The dam break flood hydrograph with peak discharge 57208.9 m^3/s creates a submergence of more than 30% area of the LTB, wherein the entire Surat city gets inundated. The developed inundation maps would be used to identify the critical infrastructure such as roadways, railways, hospitals, institutional buildings etc. across the basin.

(iv) Out of total area 326.51 km2 of Surat city, the depth of flood water more than 6 m is found on 10.92 km^2 (3.34 %) which is highly affected due to Ukai dam break of said scenario.

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